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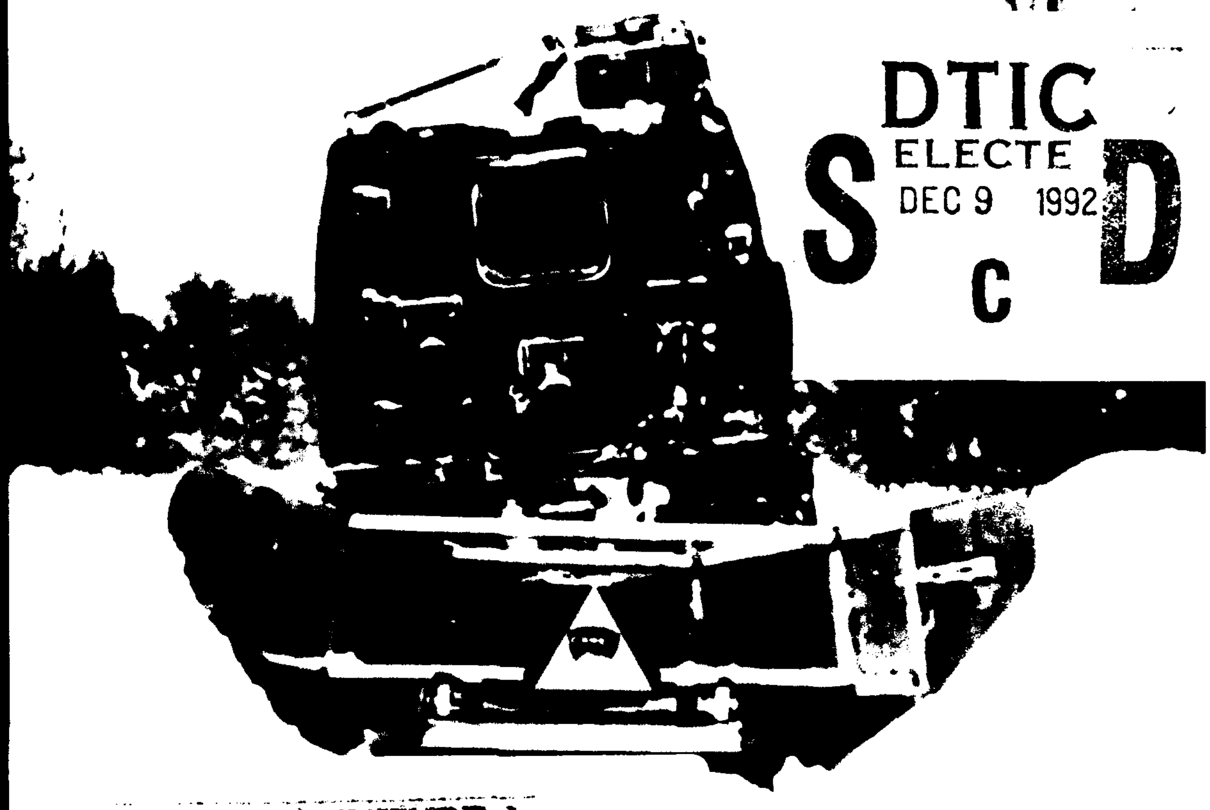
Design and Analysis of a Low Speed Drag Plow for Use in Deep Snow

Michael R. Walsh and Paul W. Richmond

September 1992



Abstract

Winter logistical operations employing wheeled vehicles are severely restricted because of traction losses in deep snow. To enable the use of wheeled vehicles for off-road winter deployment, an independent drag-plow was developed to be attached to the pintel mount of the U.S. Army's small unit support vehicle (SUSV). Small-scale testing revealed significant stability problems with a towed wedge-shaped plow model. Geometric modifications to the plow design and a 4-bar parallel motion towing linkage were developed to stabilize plow roll and pitch, respectively. A welded aluminum half-width model incorporating these modifications was successfully tested at Keweenaw Research Center in northern Michigan in January 1991. Parameters measured during testing included pitch and roll angles, drawbar forces, speed, plowed path geometry, and snow characteristics. These parameters were used to determine the feasibility of a full-scale model capable of plowing a 2.45-m path in 1-m-deep low density snow, leaving 15 cm of snow as ground cover. The model performed well in medium density snow, with drawbar forces in the 5.6-kN range. Plow penetration was limited by a geometric constraint of the 4-bar linkage, with 15° the approximate maximum link angle from horizontal. Pitch and roll stability in off-road applications was excellent, with the plow demonstrating an ability to right itself and dig in after encountering obstacles. Successful half-width tests have proven the concept of utilizing a SUSV-towed V-plow for clearing access roads in deep snow for off-road winter operations. Data extrapolation of half-width tests demonstrates that a full-scale plow is feasible.

Cover: *Half-width drag plow behind small unit support vehicle in 60 cm of dense snow at Keweenaw Research Center, Hancock, Michigan, January 1991.*

For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, *Metric Practice Guide*, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

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U.S. Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

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Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

PREFACE

This report was prepared by Michael R. Walsh, Mechanical Engineer, of the Engineering and Measurement Services Office, and Paul W. Richmond, Mechanical Engineer, of the Applied Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. This report was originally prepared by M.R. Walsh as an M.E. Thesis for the Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire.

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Design and Analysis of a Low Speed Drag Plow for Use in Deep Snow

MICHAEL R. WALSH AND PAUL W. RICHMOND

INTRODUCTION

Winter logistic operations for U.S. Army field units during the Alaskan winters are often hampered by off-road mobility problems during high snowfall years. The 6th ID(L), a light infantry division based at Ft. Wainwright near Fairbanks, Alaska, is equipped primarily with wheeled vehicles. During winter operations, accessing remote field posts that are located any distance off-road with these vehicles is extremely difficult. To more easily supply these posts and associated forces, a snow-clearing device is needed to enable standard Army wheeled vehicles, without modification, to conduct off-road winter exercises.

To address this operational problem, we designed a drag plow for use in deep snow. The fundamental requirement for our design was that the snow-clearing device should be mountable on existing equipment. The primary equipment to be considered included the U.S. Army $2\frac{1}{2}$-ton truck, the high mobility multiwheeled vehicle (HMMWV) and the small unit support vehicle (SUSV) (Fig.1). Mounting of the plow could not require any physical modification of the equipment, such as weldments, integrated power supplies, or cut-outs. The plow would not need to remove snow to ground level, as these vehicles as well as lighter ones in inventory are all-wheel drive and capable of negotiating small depths ($\leq$ 20 cm) of snow, but the finished trail would need to be wide enough to accommodate the largest of these vehicles, the $2\frac{1}{2}$-ton truck, which is 2.4 m wide.

INITIAL RESEARCH

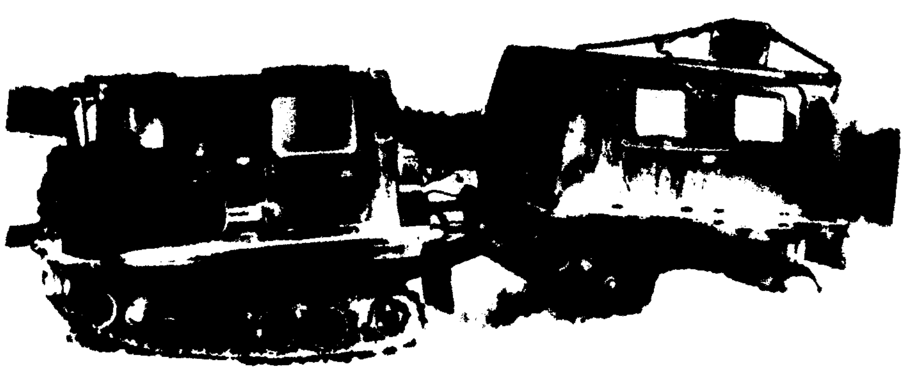
Initial research focused on an examination of current snow handling options, an investigation of the environmental parameters in Alaska, and a determination of the best option of those available. From a review of the literature, the options included rolling or compaction, blowing or throwing the snow, melting the snow, and using front or rear-mounted plows (Mellor 1965, Hoffman 1979). A field investigation was then conducted to determine which of these options would be most feasible in the central Alaskan environment.

Snow conditions in the Fairbanks region of central Alaska, where the plow would initially be deployed, differ substantially from those in the contiguous U.S. Winter temperatures are generally much lower, with temperatures rarely exceeding 0°C, and the climate drier. Because of this, the snow tends to have a density ρ below 0.2 g/cm^3 in the upper layers, while near the ground ρ is closer to 0.2 g/cm^3 due to thermodynamic processes. The warmer ground transfers heat to this "depth hoar" layer, causing the consolidation of ice crystals and an associated increase in density. During field investigations in Fairbanks in December of 1989, the snow density was found to be in the range of 0.14 to 0.19 g/cm^3. Meteorological records show that snow depths generally range from 0.6 to 1 m, with some drifts exceeding that amount. The snow tends to be very coarse grained and granular and has very little adhesion. Although it does not pack well, the snow flows easily and thus is easily moved. The terrain beneath the snow is uneven, and open areas tend to be covered with brush, hummocks, and fallen trees.

The environmental parameters found in Alaska narrowed the snow removal options to melting and plowing. Experiments previously conducted at CRREL eliminated melting because of high noise levels, large energy consumption, and low efficiency (Rand in prep.). Plowing was the one remaining option. Of the two methods of plowing

a. 2½-ton truck.

b. High-mobility multi-wheeled vehicle (HMMWV).



c. Small unit support vehicle (SUSV).

Figure 1. Standard vehicles for the light infantry division.

considered, the rear-mounted or drag plow was chosen as the best option. A V-shaped drag plow would require the least amount of vehicle modification to mount. The plow could be easily adapted to the SUSV, the only Light Infantry Division vehicle that is maneuverable in snow over 20 cm deep. It could also be designed to negotiate hidden obstacles such as logs, rocks, and hummocks.

A literature and patent search was conducted on V-plows for use in snow, with an emphasis on drag plows, but very little usable material was obtained. Most information was concerned with high-speed plows and the mechanics of fluidizing and throwing snow (Kihlgren 1961, Yosida 1980). However, one article by Price (1966) and an associated patent (1965), although directed toward front-mounted plows, proved very useful in setting design parameters for the drag-plow geometry. Other articles by Matthews (1940) and Thomas (1974) provided insight into how drag plows had previously been utilized to move snow.

Before design could begin, the design parameters had to be finalized. Depth of snow to be cleared was approximately 1 m, with a density of less than 0.2 g/cm^3. Snow left in the path could generally not exceed 20 cm, the maximum amount a HMMWV can negotiate. The most important mechanical design parameter was available motive force. As the SUSV was the only over-the-snow vehicle available, this was to be used to tow the plow.

SUSV drawbar capabilities are as follows (Richmond et al. 1990, Murrell and Shumate 1989):

Dry pavement	44.6 kN
Shallow snow (< 0.31 m):	26.8 kN
Deep snow (> 0.6 m):	13.4 kN

The plow therefore needed to clear a path in deep, low density snow at a drawbar pull of less than 13.4 kN and be able to withstand impact loads at low temperatures (–40°C), yet be light, minimizing the drag on the SUSV while plowing. The plow itself needed to be transportable over paved roads, with modular construction for ease of field repair, and have shear pins at critical points to protect the equipment. Adaptability to varying snow conditions, such as depth and density, should be possible. With these criteria in mind, a set of 1:12 scale models were built to test various drag plow configuration.

SMALL-SCALE TESTING

A series of tests using small-scale models was conducted to obtain a qualitative sense of the performance of various drag plow geometries. Tests were conducted in a 0.6- × 1.0-m box filled to the 9-cm level with a mixture of sawdust and small wood chips. The models were pulled by a single string with a 5-N spring scale. Pulling force, model stability and aggressiveness were observed. Aggressiveness is defined here as the ability to dig into the medium without loss of pitch (front to rear) stability.

The first series of tests was conducted with simple plastic wedges of 60°, 90° and 120° inclusive angles (Fig. 2). Immediate stability problems were encountered with all three designs in both the pitch and roll directions. Adjusting the tow point on the model would minimize the pitch problem, but there was no method of controlling roll. Aggressiveness was also a problem, with the models tending to ride up

Figure 2. Small-scale simple wedge models (0.46 m scale in foreground).

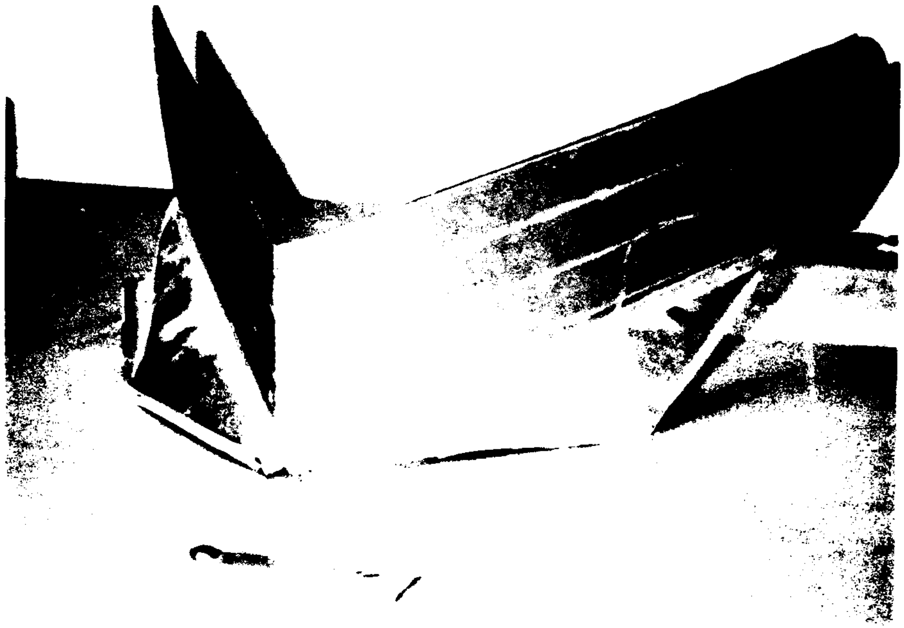


Figure 3. Modified small-scale model (height at nose: 10.2 cm).

(underaggressive) or pitch into the stratum and tip over (overaggressive). The only conclusions that could be drawn from these tests were that a simple wedge towed from a fixed point was not feasible due to stability and aggressiveness problems, and the smaller inclusive angle models tended to be easier to control, and thus more stable, than the larger inclusive angle model. Force data were inconclusive due to the instability of the larger inclusive-angle models.

A model was then designed using the previous test results and information from articles by Price (1966) and Kihlgren (1961). This model had a main body with a 60° inclusive angle and a frontal skirt blended into the main body with a 90° inclusive angle (Fig. 3). This model was tested in the same material as the previous wedge models with far more favorable results. The roll problem was minimized, while the pitch problem was easier to control but still present. Additional engineering needed to be done for pitch control. However, the overall success of the final small-scale model was encouraging.

DESIGN AND ANALYSIS OF HALF-WIDTH MODEL

With a small-scale model in hand, a half-width model was designed for proof of concept field testing. A half-width model was designed for several reasons, the primary two being cost and transportability. Many of the more expensive components for the half-width model, such as the towing mechanism, were built full-scale for interchangeability with the full-scale model should the half-width model prove the design feasible. Transportability was a major factor, as the plow would need to be shipped to a location where reliable snow could be found. After reviewing the original performance and design parameters, we chose a low weight, welded aluminum design as the best alternative for the plow itself. This design (Fig. 4) consisted of internally braced aluminum wings with a low friction coating of ultra-high molecular weight polyethylene (UHMWPE) attached to reduce friction drag (Vandrey 1977). An undercarriage with skids or wheels was used to elevate the base of the plow a fixed distance to avoid snagging ground debris.

Pitch instability was still a critical problem to overcome. To address this, a parallel-motion 4-bar linkage hitch was designed to control pitch relative to the rear SUSV unit while at the same time allowing freedom of motion for uneven terrain and turning. The design is shown in Figure 5. Features evident from the figure include the ability to adjust the plow link for varying snow depths, spring compensators in the top and lower links that allow for nonparallel motion in cases of obstacles or uneven terrain, and a hitch on the tractive end that allows motion in both the yaw (side to side) and roll

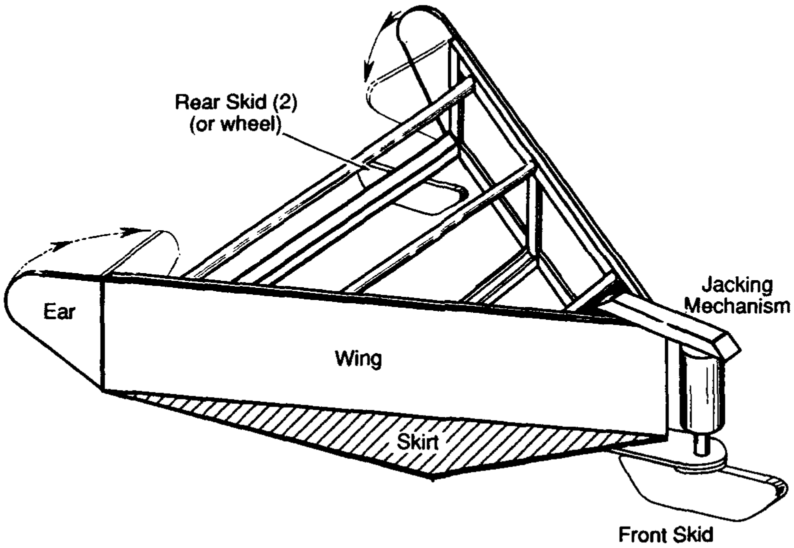


Figure 4. Sketch of half-width plow.

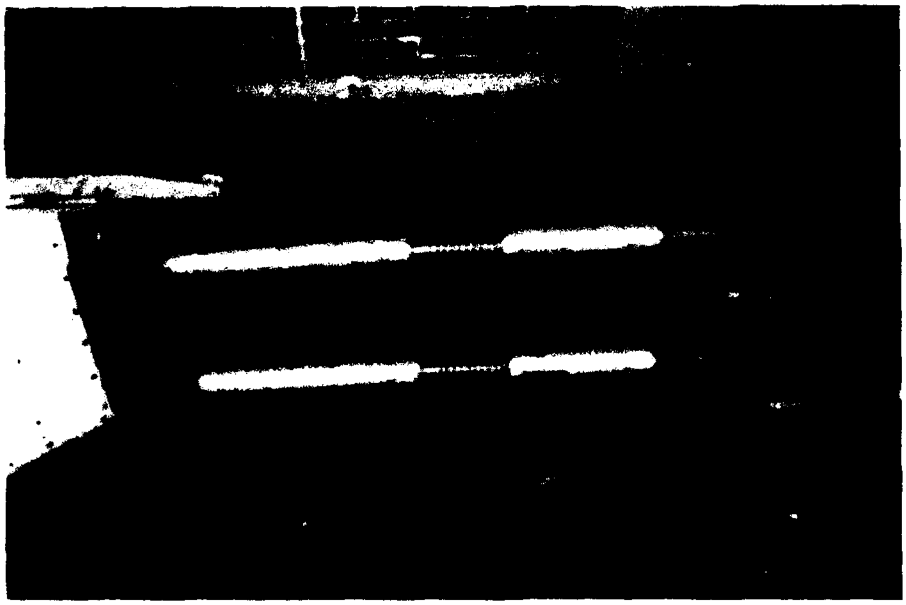


Figure 5. Towing assembly.

directions. The plow link also has freedom of motion in the yaw direction for plowing, which can be locked for towing purposes.

The pitch control towing assembly was designed for a maximum load of 44 kN, the maximum drawbar pull of the SUSV on dry pavement. Construction was of high-strength low-alloy (HSLA) steel for the ends and spring supports and thick-walled 6061-T6 aluminum tubing between, with major connections made with stainless steel pins to facilitate assembly and maintenance. Shear pins were designed into the system to protect critical equipment from impact damage. One such shear pin is located on the tractor end adapter, which allows the release of the plow and 4-bar mechanism in case of overload and facilitates mounting of the plow. A detailed discussion of the various components of the drag plow follows, starting at the tractor adapter and working back to the plow. Appendix A contains assembly drawings of major components for further reference.

The tractor adapter (Fig. 6) attaches to the pintel hook mount on the rear unit of the SUSV. Removal of the pintel hook can be accomplished in about 5

Figure 6. Tractor adaptor.

minutes, with mounting of the adapter taking about the same. The adapter is constructed primarily of HSLA steel for its high strength to weight ratio. The assembly must be stiff, as it allows two rotational axes of freedom: roll and yaw. Roll is necessary to allow for uneven terrain, and yaw for cornering. SUSV design roll is 40° and yaw is 24° (for an 8-m turning radius), both of which can be accommodated by this adapter. Flat bearing surfaces are PTFE on steel (coefficient of friction $u = 0.04$) while rotating bearings are constructed from a PTFE fabric composite bearing. Bearings are designed for 44-kN loads and low speeds, and they do not require lubrication, thus avoiding a major cold climate problem. Pins and removable hardware are constructed of stainless steel (304) to prevent corrosion. The adapter acts as the ground link in the parallel motion 4-bar linkage.

The top and lower links connect the tractor to the plow (Fig. 5). These links provide the parallel motion critical to the pitch stability of the plow. These links are also designed to accommodate the 44-kN drawbar force of the SUSV. Provision was made for load cells to be mounted on both links and for a tilt sensor to be mounted on the top link (instrumentation will be discussed later). Another feature of this assembly is a terrain compensation spring in the center of each link. These springs allow compressive link length variances in cases where the plow encounters an obstacle or the terrain is uneven. For the half-width model, a spring with a rate of 1 kN/cm

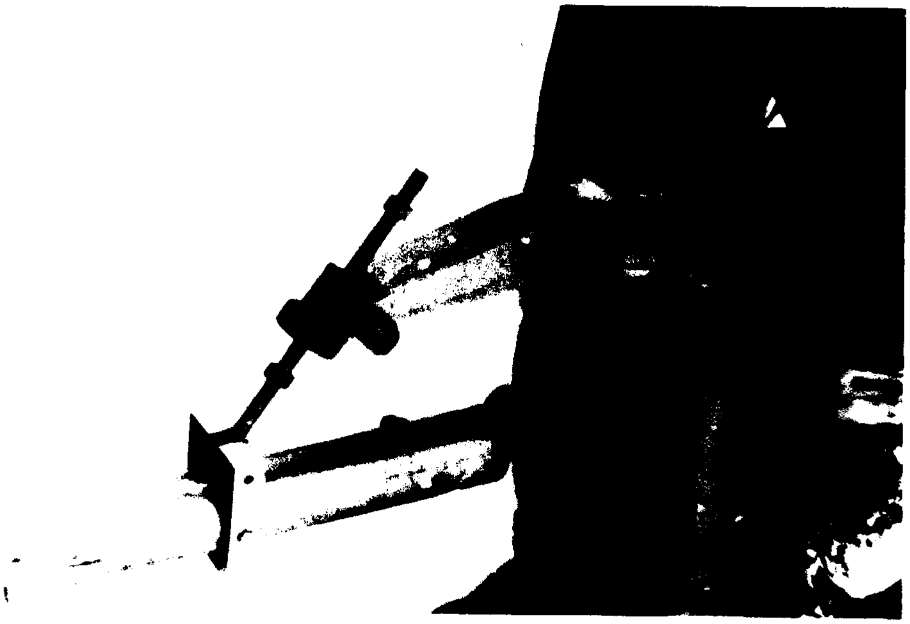


Figure 7. Top link jacking mechanism.

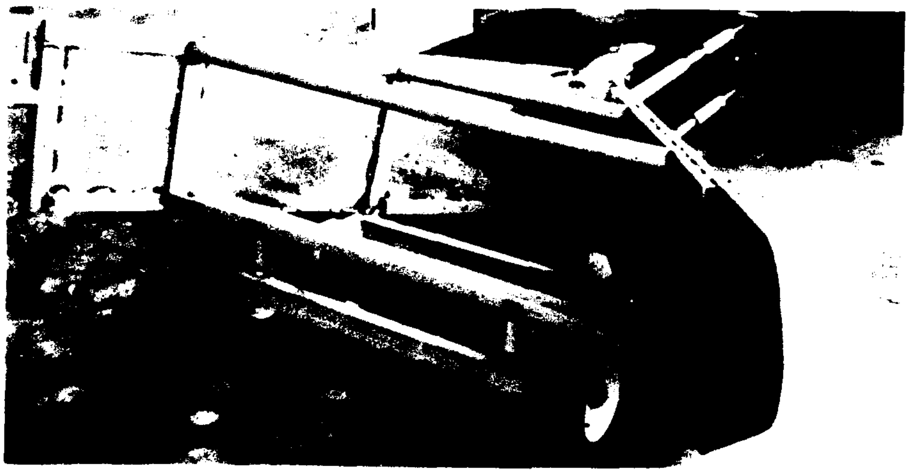
was used in each link, while 1.9-kN/cm springs will be used for the full-scale model. Travel for these springs is 5.6 and 7 cm, respectively, allowing an angular deviation of 10.4° for the half-width and 12.9° for the full-scale model. This allows scaling a 23-cm obstacle with the half-width plow without overstressing the equipment.

The plow pivot assembly or plow link is the fourth member of the 4-bar mechanism. This assembly includes the front elevating skid of the plow, which turns with the link relative to the plow in the yaw direction. This rotational degree of freedom can be locked with a pin for ease of highway transport. The plow link is also adjustable in the vertical direction to accommodate increased snow depth or density. This allows for more efficient use of the SUSV tractive power and reduces vertical lifting forces on the nose of the plow. The front skid, which pivots with the plow link, serves to control the maximum depth of plowing and protects the front of the plow from damage that could be caused by ground debris. It, in turn, is protected by a shear pin in the yaw (torsional) direction rated at 22 kN.

For highway transport, a jacking mechanism was devised to lift the front skid off the ground (Fig. 7). This is a simple three-member assembly that allows a change of length of one of the members, thereby lifting the skid. This mechanism acts on the top link, with the change in angle between that link and the plow link causing the skid to rise. The lower link spring compensates for the nonparallel configuration of the 4-bar mechanism during towing.

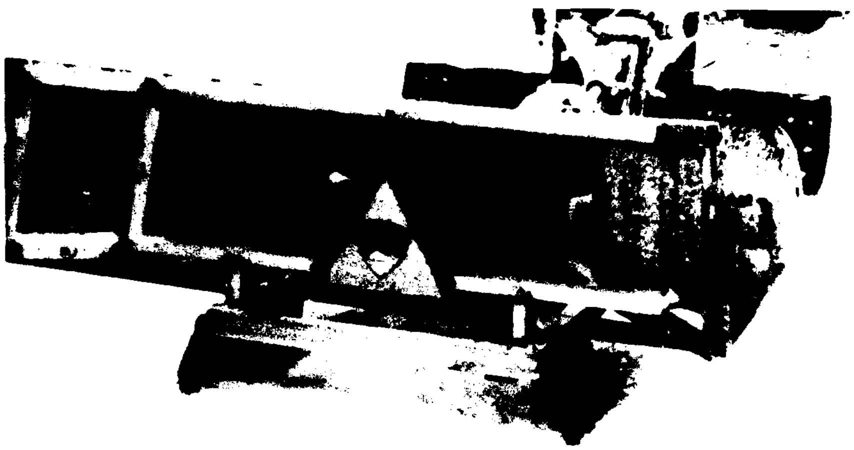
The plow, as previously stated, is of welded aluminum construction. Aluminum was chosen for its light weight and impact strength at low temperatures. The main segments of the plow, the skirt, wings, and folding ears (extension of the wings beyond the skirt), are constructed of aluminum plate overlaid with UHMWPE. The half-width model has a 6.6-mm-thick skirt with 4.8-mm-thick wings and ears. The UHMWPE sheet stock covering the aluminum is of the same thickness as the aluminum it covers. Bracing between the wings consists of aluminum tubing and channel welded to the wings to provide structural rigidity. Triangular plates were welded to the inside of the nose of the plow for strength. The ears were designed to fold inward to reduce plow width during highway transport. A simple sliding bar "bolt" locks them in place.

The rear elevating assembly had to accommodate travel both on and off-road. To accomplish this, a trailing arm arrangement was designed with stub axles and hubs for wheels. Skids were then designed to fit on the hubs for off-road use (Fig. 8). Both wheels and skids protrude 11 cm below the plow, which will result in a layer of snow on the ground approximately half the 20-cm maximum for wheeled vehicle maneuverability. A forward-locking point was provided to allow pinning the nose of the rear skids, thus preventing them from rotating on the stub axle.



a. Wheel configuration.

Figure 8. Rear plow supports.



b. Skid configuration.

Figure 8 (cont'd). Rear plow supports.

The basic plow geometry was developed using the results from the small-scale tests and a review of work by Price (1966) and Kihlgren (1961). The most efficient designs for low speed plows described by these researchers were consolidated, simplified, and applied to the small-scale test results for the half-width drag plow. The geometry of the plow is determined by three angles (Fig. 9): the wing inclusive angle (α), the skirt inclusive angle (β) and the skirt azimuth angle (γ) between the ground and the skirt, along the intersection of the leading edge of the skirt. Minimum drag force during plowing was found to occur with the smallest wing angle (α) during $^1/_{12}$ scale tests. For practical purposes, α should not be less than 60°. Less than that, and the plow becomes excessively long. The skirt angle (β) was chosen to be 90° for ease of design and fabrication. It was also within the design limits suggested by Price of 80° to 100° for highest efficiency. The skirt azimuth angle (γ) of 35° was taken directly from Price (1966). The three major stability axes, pitch, roll, and yaw, are referenced in the figure.

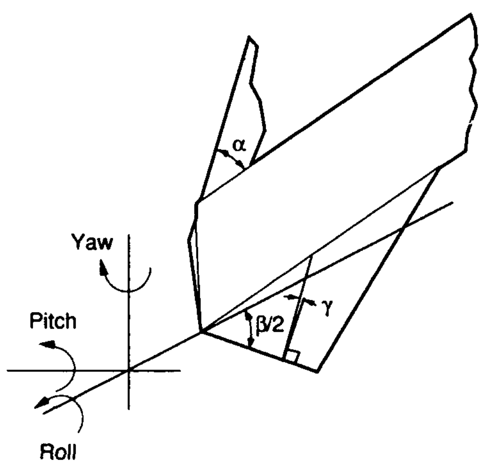


Figure 9. Plow geometry critical angles.

With the basic angles fixed, the remaining geometry of the plow was determined using the operating parameters (Appx. B). Path width was the controlling factor, along with design snow depth. For the half-width model, these values were 1.22 and 0.6 m, respectively. In analyzing for the best geometry of the plow with respect to these parameters, we assumed an angle of repose for light, dry snow of 45°. (The angle of repose for the snow encountered in Alaska was approximately 45°.) To reduce the size of the skirt and thus the length and span of the wings ahead of the ears, the plow was designed to initially clear a 1.5-m-wide path with 60° sloped sides, which would collapse to form a 1.22-m-wide path with 45° side banks. This reduces the width of the half-width plow by 0.5 m between the wing ends for road transport. The transport width of the half-width plow is 1.9 m using this design.

The height of the plow at the nose is 67 cm from ground level, with 11-cm clearance between the ground and the bottom of the plow. The angle formed by the intersection of the skirt with the wings is 10.27° relative to the ground, which was carried through to the upper wing edges, giving a wing depth of 56 cm. After completion of the geometric design calculations, stress analyses were carried out on the critical members of the structure.

As these are quite lengthy, they are included as an appendix (App. C).

Design loads for the tractor adapter and 4-bar parallel motion mechanism were taken as full-scale (44 kN). The weight and center of gravity calculations done during the geometric design process were used in analyzing the plow and other half-width assemblies. Using these geometric and load data, we analyzed assemblies and components in succession from the adapter to the rear skids. Any design change necessitated by forces on a specific component was worked back on previous components and assemblies until a final design was achieved.

The last step in the fabrication design analysis was to predict the behavior of the system. From small-scale testing, the design seemed quite stable in the roll direction. The skirt acted as a stabilizer for the wings, with the load of the displaced material on the skirt damping any tendency for the plow to tip. The skirt also acted to draw the plow into the sawdust and woodchip mixture, increasing its ability to remove snow from the projected path.

Approximately 80% of the weight of the snow above the skirt will act downward, forcing the plow to the ground. For an effective area of 0.7 m^2, a snow density above the skirt of 0.35 g/cm^3, and a snow depth of 50 cm of plowed snow, this calculates to a force of 0.9 kN acting on each skirt. The plow weight alone is 252 kg, resulting in a total downward force of about 3.4 kN. This force is counteracted by the vertical component of the drawbar pull, which is a function of the top link angle. For a 15° angle with a 5.0-kN horizontal force component, the vertical force component will be on the order of 1.3 kN. Not considered here is the buoyant force of the understructure of the plow on the snow surface or vertical forces on the rear of the plow as it forms the sloped banks.

Horizontal or drawbar force is estimated from empirical data from Price (1965). Using his most efficient plow design and scaling back to the half-width model to be used in these tests, we expected a force of approximately 5.4 kN. This did not take into account drag due to skids, which should be minimal (<40 N). For 0.6 m of low density (< 0.2 g/cm^3) snow, SUSV sinkage should be on the order of 40 cm (Murrell and Shumate 1989). Towing angle should be approximately 14° for these conditions.

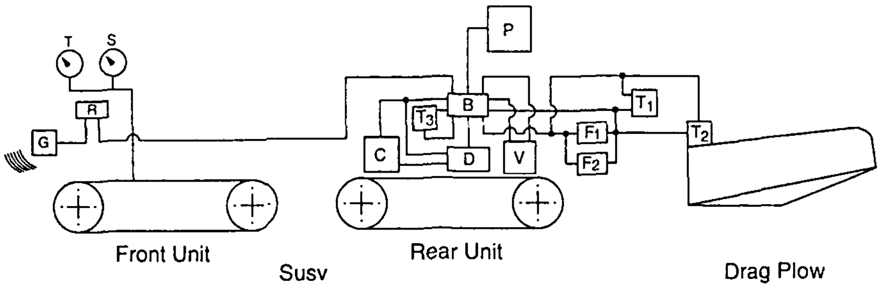
INSTRUMENTATION

The half-width prototype plow was built to test the feasibility of a larger drag plow. Quantitative knowledge of the dynamic characteristics of the model in the field was therefore very important in assessing the viability of the concept. A set of critical parameters was determined and an instrumentation package assembled.

There are several factors that will affect the performance of the drag plow. The most obvious is drawbar force, the limiting factor for the tractor. Drawbar force will be equivalent to the drag or resistance of the plow as it is pulled through the snow. A second related parameter is stability, both in the roll and pitch direction. As discussed earlier both pitch and roll stability will affect the efficiency of the plow. The relative angle of the top and lower links with the tractor will also determine the horizontal and vertical forces applied to the plow. Speed of plowing is also important, both from a drag and tractive viewpoint. Very low speeds may incur stick-slip frictional forces, whereas higher speeds may incur larger towing forces due to the resistance of the snow to flow and an associated increase in the vertical force component on the towing mechanism which may cause the plow to ride up. Snow conditions were the final factor to be considered. Snow depth and density will affect the drawbar force as they are directly related to mass of snow moved and tractive force available.

The instrumentation layout used for testing is shown in Figure 10. It can be divided in four parts: the power supply, data acquisition system, sensors, and SUSV instrumentation modules. The power supply module consists of a 2200 W, 120 V AC, 60-Hz single phase generator, 12-V and dual voltage (0 to 6 V, 0 to 20 V) variable DC power supplies, and a power distribution bus. The data acquisition system (DAS) consists of an Elexor PL-1000 DAS, with digital and analog input boards, and a laptop computer. Sensors include load cells, tilt sensors, and an ultrasonic speed sensor with digital readout. SUSV instrumentation used during testing consisted of the vehicle's tachometer and speedometer.

The load cells used to measure drawbar forces in the top and lower links were Sensotec model RM 10,000-lb (44.3-kN) in-line load cells, requiring 10-V DC power. Output is 2-mV/V analog DC signal, 20-mV full scale. They are of a bonded foil strain gauge construction with 350-ohm bridge resistance. The gauge is mounted to an I-beam structure centrally located in the sensor for increased accuracy. A force on the sensor distorts the bridge, causing a change in resistance. This potential change, when divided by a laboratory-derived calibration factor, gives a signal directly proportional to force. Com-



T: SUSV Tachometer	P: Power (Generator)	T1: Top link tilt sensor
S: SUSV Speedometer	B: Power/instrumentation bus	T2: Plow tilt sensor
R: Speed sensor readout	V: Voltage sources (10, 5, & 12 V)	T3: SUSV rear unit tilt sensor
G: Ultrasonic speed sensor		F1: Top link load cell
	D: Data acquisition system	F2: Lower link load cell
	C: Computer	

Figure 10. Instrumentation layout.

plete specifications on this and other instrumentation are given in Appendix D.

Tilt sensors were used to measure the angle of the top link pitch and plow roll or rear unit pitch. Only two sensors (General Oceanics model 6020 tilt/acceleration sensors) were employed during any one test. Input power was 5 V DC, while output was analog ± 2.5 V DC (± 90°). The sensors are of a force-balance design, with a pendulum causing a moving coil to be displaced. This displacement is sensed and current is applied to bring the coil back to the null position. The current required is fed into a buffer amplifier to generate the output signal, which is sinusoidally related to the angle.

The speed sensor used in this research was a Micro-Trak Trak-Star ultrasonic speed sensor. A 12-V DC input was required to power the sensor, while the output signal was digital. The sensor measures the distance to an object by calculating the temperature-compensated time differential between transmission and reception of a high frequency sound pulse. By inverting, the time differential becomes frequency. Ten samples are averaged to smooth the signal, which is transformed to a digital pulse by the sensor electronics. Calibration is 11.36 Hz per m/sec. This is the first application to our knowledge of this sensor system being used in snow. It is normally used by farm machinery while tilling soil.

In the forward unit of the SUSV, the engine tachometer, speedometer, and digital readout for the speed sensor were used to maintain test speeds. The tachometer was very useful, as it was the steadiest indicator of vehicle speed, especially on the hard snow roads. All three indicators were checked against each other to verify operability.

Before the instrumentation and plow were taken to the field, test and calibration work were performed at CRREL. Although the lack of snow limited the amount of testing that could be done, most systems were evaluated before field use. Both the load and tilt sensors were calibrated at the lab. The load sensors were calibrated in a load frame against a precalibrated load cell, traceable to the National Institute of Standards and Technology. The theoretical scale factor for the load cells was derived in the following manner:

Range:	±44.6 kN
Excitation voltage:	10 V DC
Load cell output:	±20 mV
Gain setting, DAS:	100 ×
DAS full-scale:	4096 counts
DAS full-scale input:	±2.5 V
Load cell F.S. counts:	~3280 (89.3 kN)
Theoretical DAS scale factor:	0.037 counts/N

Scale factors derived during calibration were 0.039 for the top load cell and 0.038 for the lower load cell. The load cells were calibrated in the range from 0 to 13.4 kN, over twice the maximum range predicted for plowing.

The tilt sensors were calibrated using a digital protractor with an accuracy of $1\frac{1}{2}$% of reading. Sensors were tested to ±90° with agreement to less than 0.4°. Input voltage was 5 V DC, and output ±2.5 V DC full scale (±90°). A problem occurred in that the analog voltages for the load cells and tilt

Table 1. Load cell test data.

*Load** *(kN)*	*Top link* *(kN)*	*Low link* *(kN)*	*Load†* *(kN)*	*Error* *(%)*
0	0	0	0	0
1.54	1.25	0.25	1.5	2.6
2.43	2.0	0.5	2.5	2.8
4.71	4.0	0.75	4.75	0.8
0	0	0	0	0

* Calibrated load cell
† Top and lower cells summed

sensors vary by two orders of magnitude. As noted above, full-scale input for the DAS is 2.5 V DC and the gain had already been set at 100 to accommodate the low load cell output voltage. A 100:1 voltage divider was therefore connected into the tilt sensor circuitry before the analog DAS input to enable full-scale reading of the sensors. The sensor output angle was derived in the following manner by the data acquisition system:

Range:	90°
Excitation voltage:	5 V DC
Tilt sensor output:	±2.5 V DC
DAS full-scale:	4096 counts
Theoretical DAS scale factor:	0.8 counts/mV_{out} (180 degrees)

The angle is not linearly convertible to the tilt angle due to the sensor electronics. For calibration purposes, the relationship was:

$$\beta = \sin^{-1}(V/2.5)$$
$$\beta = \sin^{-1}(mV/2500)$$
$$\beta = \sin^{-1}[(counts/2048)-1] \quad (1)$$

Sign convention is (+) for the SUSV rear unit higher than the plow, and (–) otherwise.

The operability of the speed sensor electronics was tested using a frequency generator. For normal operation, output is calibrated by the manufacturer at 3.18 Hz/kilometer per hour (kph). No lab calibration of the system was possible, although testing on dry pavement against a fifth wheel speed indicator was attempted. Speed could not be held constant enough to obtain sufficient data to do a statistical analysis of the error.

Field testing of the equipment at CRREL was carried out next. The load cells and tilt sensors were installed on the plow, which in turn was attached to a 3/4-ton, four-wheel drive pickup truck bumper via an adapter for the tractor hitch. The rear of the plow was attached to the calibrated load cell, which in turn was chained to a concrete post. Using a 10 V DC power supply, digital multimeter, strip chart recorder, and the calibrated load cell, the top and lower load cells were checked for accuracy (Table 1). Loads of 1.54, 2.43 and 4.71 kN, read from the calibrated cell, were applied to the structure by inching the truck forward. Error in this load range was less than 3%.

The equipment was then taken to a nearby field with about 10 cm of crusty snow for drag tests and to check out the data acquisition system. The plow, with skids at the rear, was pulled along the field at low speed with the DAS operating. Tracking (Fig. 11) was quite good, with the plow falling in the center of the truck tracks and easily negotiating turns. The DAS also performed well, and resultant drawbar forces were about 0.7 kN. The speed sensor was also checked at this time over snow. The sensor output and readout and the truck speedometer agreed at low speeds (<16 kph) and thus the sonic speed sensor was presumed acceptable for

Figure 11. Towing tests: tracking.

testing purposes. With the laboratory calibration and test work completed, the equipment was judged ready to ship to upper Michigan for field testing.

FIELD TESTS OF HALF-WIDTH MODEL

Field testing of the half-width drag plow was conducted at the Keweenaw Research Center (KRC) located in Hancock, Michigan, on the Keweenaw Peninsula of the Upper Peninsula. This facility is operated by Michigan Technological University in Houghton for the U.S. Army. Dedicated to mobility studies, KRC has been in existence for over 30 years.

Testing was conducted between 17 January and 28 January 1991. Five series of tests were run, with quantitative data collected during four of those sessions. The fifth was devoted to obtaining video and still pictures of the equipment in operation. Tests could be divided two different ways, depending on rear plow support configuration—wheels or skids (Fig. 8)—and type of test conducted. The majority of testing done was with rear skids, as initially this seemed a more feasible configuration than utilizing the plow with wheels. Test types included baseline, drag, plowing, and replowing.

Initial snow conditions were very close to those desired. Snow depth was 40 to 70 cm and density was 0.2 to 0.3 g/cm^3, a little denser than the 0.15 to 0.2 g/cm^3 which was found in Alaska. Air temperature was around –10°C with some wind. Weather conditions quickly deteriorated, however, warming to about 5°C, which caused the snow to rapidly densify. A cold, windy period followed with temperatures below –15°C, causing the snow to freeze with a 0.6-cm surface layer of ice. Snow densities after the thaw/freeze cycle approached 0.4 g/cm^3. About 20 cm of light, dry snow then covered this layer of ice.

Baseline tests were conducted on a packed snow road called the Access Road (Fig. 12). The objectives of these tests were to find the non-plowing towing resistance in different configurations at various speeds and to generate a database that could be used for comparison of system characteristics over the course of testing. The tests also proved valuable in checking the operation of the instrumentation and data acquisition system. Drag tests were conducted in the Texas Flats, a packed area ($\rho \approx 0.4$ g/cm^3) with 10 to 13 cm of snow cover. The purpose of these tests was to determine the drag caused by the supporting structure beneath the plow. Plowing tests were conducted both off-road and over unplowed roads, while replowing tests were conducted over previously plowed paths which had not cleaned up to within 13 cm of ground level. Plowing tests were conducted adjacent to and within the Texas Flats area, in the Test Road Circle, and along and adjacent to an unplowed stretch of the Test Road. For the purpose of this report, testing will be divided into two categories, wheels and skids.

Plow operation with skids

Extensive field testing was conducted with the drag plow in the skid configuration. Included were baseline tests at various speeds and with two different front skids, drag tests along a straight and curved path, plowing tests under various snow conditions, and replowing tests over previously plowed paths. Qualitative data were also gathered using video and still camera equipment to record plowing tests. Typical data acquisition spans were 15 seconds in length, corresponding to a traveled distance of 20 m at 4.8 kph (66 ft at 3 mph). Drawbar forces opposing the motion of the tractor are given as negative in graphs, as this was how data were collected. Otherwise, they are presented as positive. Complete data sets are contained in CRREL Internal Report 1098 (Walsh 1992), while Appendix E summarizes the tests described in this section.

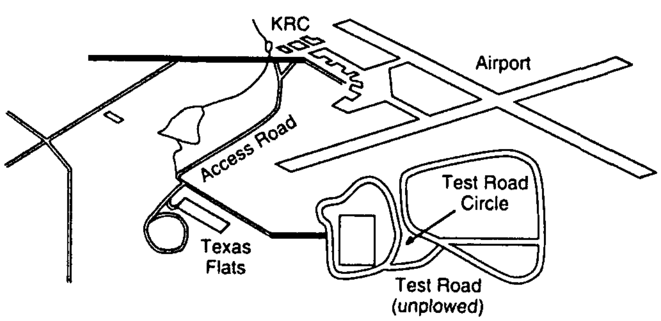


Figure 12. Keweenaw Research Center layout.

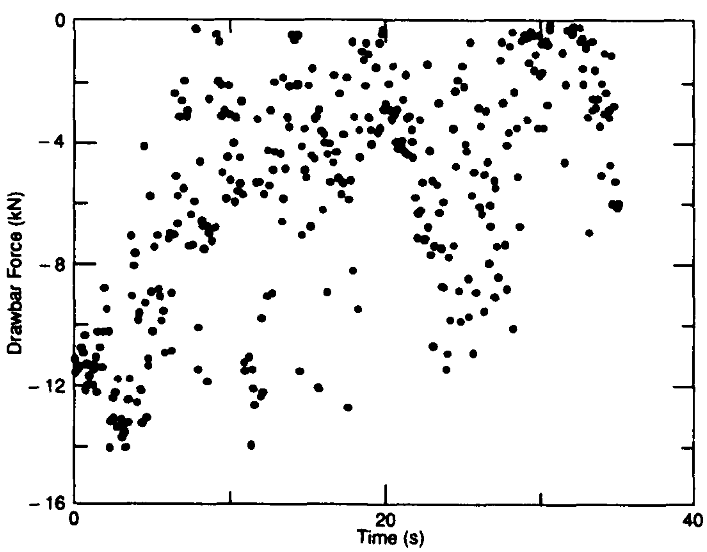
Table 2: Skid test data summary.

Test	*Drawbar force (kN)*	*Skid penetration (cm)*	*Plow penetration (cm)*
Skid resistance	0.6	2.5	0
Drag	1.1	11.5	0
Plowing	2.8	13	31
Replowing	2.5	13	15

Baseline skid resistance tests were all run on the Access Road (Fig. 12). Tests were run on 19, 26 and 28 January, with data from the 28th not usable because of extreme scatter. Extensive testing was done on the 19th with runs at various speeds from 1.45 to 11.5 kph. A synopsis of these data, along with other skid test data, is presented in Table 2. Tests conducted on 19 January were done with damaged skids (damaged during plowing tests conducted on the 17th) in soft snow and an ambient temperature of about 5°C. Drawbar forces were on the order of 0.6 kN. The tests on the 26th were done with steel skids at low temperature (–11°C). Drawbar forces were about 0.3 kN. Plow speed did not have a significant effect on the drawbar force, although higher speeds averaged lower forces. Forces on the 26th were significantly lower than those on the 19th due to the harder road surface and smoother skid bottoms. Baseline resistance can be estimated at around 0.3 kN in conditions similar to those in Alaska at speeds between 1.8 and 11 kph.

Drag tests were conducted in cold, packed snow at Texas Flats. Two tests were run at about 5.4 kph. The first was straight line and the second a long, curving test. In both tests the skids sank into the snow to the base of the plow.

Plowing tests can be divided into two categories: plowing "new" snow and replowing over a previous path. New snow does not necessarily mean fresh, unpacked snow. Only one plowing test can safely be considered to have been done in snow that had not been disturbed. That was 26J15f, which took place off the Test Road. Drawbar force for this test plowing 37 cm of snow averaged 3.1 kN. Testing done adjacent to Texas Flats, 17WH07f, was done partially in unmodified snow, although near the end of the test the plow encountered machined, hardened snow (Fig. 13). Forces for this test averaged closer to 5.6 kN, while plowed depth was up to 50 cm in drifted locations. Tests in general were conducted at or near 4.8 kph. This speed was attained at the maximum recommended sustained



a. Drawbar force during plowing test.

Figure 13. Texas Flats plowing test.

b. Plowed path (1-m rule).

Figure 13 (cont'd). Texas Flats plowing test.

engine speed for the SUSV in low gear, low range. It was also the maximum safe speed for the driver with the attached drag plow, and allowed an observer to follow the test on foot.

After several tests on the 25th and 26th, it was apparent that, under certain conditions, the plow would float in the snow and not plow to the ground. Tests were run on the 26th to evaluate the effectiveness of replowing these paths. As with the plowing tests, various speeds were tried, with 4.8 kph being the preferred or target speed. Loads and tilts were monitored and path depth checked.

Plow operation with wheels

As originally configured, the drag plow was to be operated with wheels in place of the rear skids. This would obviate the need for a mechanism for changing from wheels, necessary for over-the-road transport, to skids for off-road operations. It would also provide a guiding path for follow-on vehicles, prepacking a trail for the wheeled vehicles. Tires similar to those used on the HMMWV, 36 × 12.5–16.5 LT, were to be used on the full-scale plow as they would provide a path which the vehicle could easily follow. The full-scale model was estimated to have rear support vertical loads of about 140 kg. Using equations derived by Richmond et al. (1990) for wheel mobility in snow, we can estimate the tire sinkage:

$$
\begin{aligned}
z &= h \times [1 - (\rho_o/\rho_f)] \\
&= 20 \times [1 - 0.2/0.5] \\
&= 12 \text{ cm}
\end{aligned}
\tag{2}
$$

where z = sinkage (cm)
h = snow depth (20 cm)
ρ_o = initial snow density (0.2 g/cm^3 from field measurement)
ρ_f = final snow density (estimated to be 0.5 g/cm^3 from empirical data)

This value is used to estimate the rolling resistance of the tire, using the following relationship (Richmond et al. 1990):

$$Y = 100.75\ X^{0.59} \tag{3}$$

where $X = \rho_o \times \omega_t \times L$
Y = net resistance (in newtons)
ω_t = tire width (33 cm)
L = arc length of snow contact with the tire.

In this case, with z derived from above, L = 44.9 cm. Using these values, a net rolling resistance of 2.9 kN

Table 3. Wheeled configuration performance (See Appendix F).

Test	*Drawbar force (kN)*	*Penetration wheels (cm)*	*Penetration plow (cm)*
Rolling resistance	0.1	< 1	0
Drag	1.0	< 2	0
Plowing	1.6	13	15

Figure 14. Plowing with wheels.

was derived for each HMMWV wheel, for a total resistance of 5.8 kN.

With a drawbar pull of 13.4 kN in deep snow for the SUSV and an estimated drag of 7.1 to 10.7 kN for the full-scale plow, two problems become evident from this analysis. The first was that the wheels do not sink to the ground, due to flotation of the tires in the snow. This would limit the penetration of the plow and might cause the plow to ride up, especially when denser snow is encountered. The second problem was the increase in drawbar pull. With this added load, the SUSV had little or no reserve tractive force available.

Nevertheless, half-width tests were run in the wheeled configuration to confirm the predicted performance. As with the skid configuration, three basic tests were run: rolling resistance baseline tests on the hard-packed access road, drag tests on the lighter but deeper packed Texas Flats area, and a plow test on the undisturbed test road (Table 3). Rolling resistance and drag tests were initially encouraging, with drawbar force values comparable to the skid configuration (Table 2). However, plowing tests, as expected from the previous analysis, showed the weakness of this concept. While efficiently plowing the light upper layer of snow ($\rho < 0.2$ g/cm^3), the wheels rode on top of the denser snow ($\rho \approx 0.37$ g/cm^3), causing the plow to remove only 15 of 70 cm of snow in that area (Fig. 14). With the test data and observations confirming the predicted outcome, the wheeled configuration was no longer pursued as an acceptable option for the half-width plow.

ANALYSIS OF DATA

Analysis of the data reveals three significant findings. The first is that the plow is stable. Snow depth measurements and performance characteristics indicate that the plow is quite stable in the roll direction, not tipping significantly to either side, and in the pitch direction, neither tipping forward and digging in excessively nor riding up. The second finding is that the plow doesn't always clear to the desired depth. This is especially evident in denser snow. The third is that drawbar loads are in the range anticipated. This applies to the skid configuration. As previously indicated, the wheeled configuration is not an option, although it will be discussed briefly later.

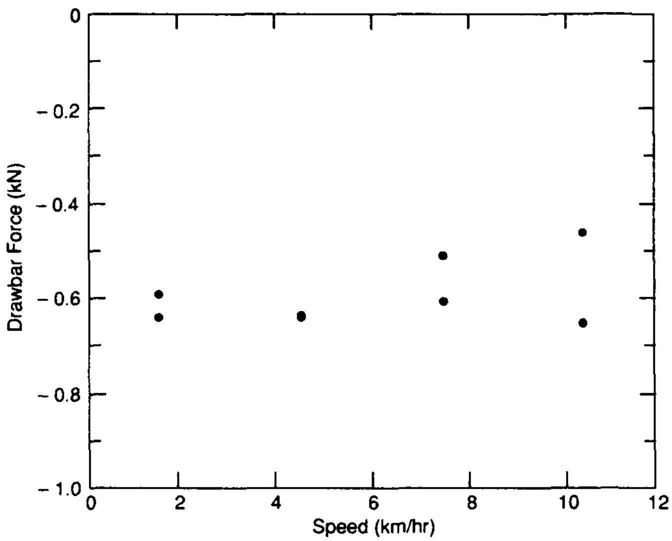


Figure 15. Baseline skid data: variable speed.

Baseline skid data taken during tests on 19 and 26 January showed only a slight reduction in drawbar forces with increased speed and the influence of snow and skid condition on drag force. Figure 15 shows drawbar force vs speed for tests run on 19 January. Forces, shown as negative as they oppose the tractor, are generally in the 0.6-kN range. Soft snow conditions existed that day, and the skid bottoms had been badly damaged during testing on the 17th. With new equipment on colder, drier snow, drawbar forces were reduced by 50% to 0.3 kN. The tests on the 19th demonstrate that speed does not have a significant effect on baseline drag, while comparison to those on the 26th show that snow and skid conditions do.

Skid drag analysis is straightforward. Both tests were consistent, with drag approximately 1.1 kN at 5.4 kph. Drag is more important in estimating plowing forces than baseline forces because the plow does not necessarily contact the ground at all times, as was found during later testing. To obtain the actual drag forces exerted by the plow skids due to horizontal interaction with the snow, the baseline forces, a measure of the friction force of the skid on the snow, must be subtracted from the drag measurement. This leaves a net actual drag on the order of 0.8 kN, which will be experienced by both the half- and full-scale model plows.

Analysis of plowing can be done from two perspectives: forces and penetration. Although there was more interest in drawbar forces for scaling purposes, plow penetration is also critical and proved to be a better indicator of plow performance. An in-depth analysis of penetration vs. performance was therefore conducted. The original design criteria for the plow indicated that operations would take place in snow with a density of less than 0.2 g/cm^3. At KRC, densities ranged from 0.22 to 0.39 g/cm^3, with a thick ice layer ($\rho \approx 0.9$ g/cm^3) encountered during later tests. This had two effects on testing: the weight of snow moved for a given volume was greater, and the SUSV, with a ground pressure of only 12 kPa, sank less in the denser snow. Testing in Alaska indicated that the SUSV sank 27 cm in 45 cm of snow, whereas in Michigan, sinkage ranged from 12 to 24 cm in snow that was 38 to 71 cm deep. Sinkage will result in decreased available tractive force due to increased forward motion resistance of the SUSV, but also decreased relative depth of the plow to the rear SUSV unit.

In tests run at KRC, the limiting factor for plowed depth was more closely related to snow density than drawbar force. The angle of the top link, a function of SUSV sinkage and plow depth, was limited to between 15° and 17° (Table 4). Drawbar force had an inverse relationship to plowing depth,

Table 4. Snow density and plow performance.

Snow density (g/cm)*	*SUSV sinkage (cm)*	*Plow penetration (cm)*	*Snow mass* (kg)*	*Link angle (degrees)*	*Drawbar force** (kN)*
0.21–0.29	25	38–51	200	15	5.6
0.31	16	30–36	190	17	2.5
0.36–0.39	12	23–28	140	15	2.4
0.41†	0	15–20	70	15	2.5

* Calculated
† Replow data
** Averages

Figure 16. Towing assembly during deep plow.

if any at all. Simple trigonometric analysis of the forces show that at 15°, the vertical force on the nose of the plow is 0.26 times the force along the link while the drawbar force is 0.97 times the force along the link. For a 5-kN drawbar force, the vertical force on the nose was 1.3 kN. The static weight on the nose of the plow was measured at 0.7 kN, so that the net effective lifting force is 0.6 kN. Although plow pitch angles were not measured, there is photographic evidence that some lifting of the plow nose occurred (Fig. 16). The compensation springs located in the lower link allowed this angular displacement of the nose of the plow. Force data on the two links confirmed this, with a tensile force on the top link and a compressive force on the lower link, indicating distortion of the 4-bar linkage.

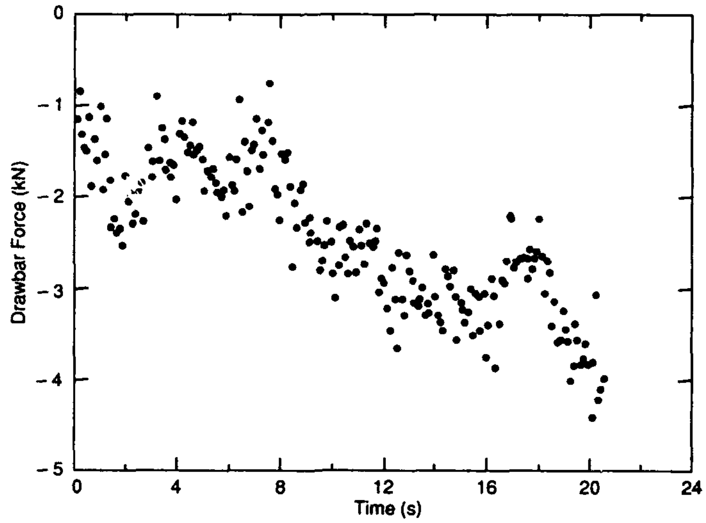
The vertical force component and its effect on the pitch angle of the plow do not, however, fully explain the 15° link angle phenomenon. The deepest paths were plowed when the vertical force was largest, while the inverse was also true. Both cases had the 15° factor in common. This geometric property of the system is probably the result of several factors, including snow density, compactability and shear strength of the snow, and vertical weight of the snow on the plow. Analysis of these factors is beyond the scope of this research. However, designing around this 15° constraint is quite possible, and alternative design concepts will be discussed in the next section.

Table 5. Topography of off-road plowing test.

Distance (meters)	*Plowed depth (cm) Left skid*	*Right skid*	*Differential (cm)*
0	38	33	5
1.2	33	36	3
2.5	41	38	3
3.7*	28	46	18
5.0	38	33	5
6.2	36	38	2
7.5	33	36	3

* Approximate location of obstacle

Roll stability, a major concern due to the instability of the original 1:12 scale models, was not a problem during field tests. The plow geometry, with the skirt protruding from the wings, acted to stabilize the plow. The plow tended to follow surface topography, penetrating to similar depths on each side of center, until ground was encountered. Variances of 6 cm in the remaining snow cover were not unusual on uneven terrain, whereas differences of only 1 to 3 cm between the sides were generally found when plowing over the test road. The most significant finding was the tendency of the plow to right itself after encountering obstacles. During off-road testing near the Test Road, a 33-cm object frozen to the ground caused the plow to lurch badly. The plow righted itself and dug back in within 2 m of the encounter. Subsequent depth measurements depict a stable path form (Table 5).



a. Increasing force due to snow accumulation in path.

b. Photograph showing snow accumulating in path.

Figure 17. Replowing test.

Drawbar forces varied widely throughout the plowing tests but tended to fall in the 2.2- to 3.6-kN range. The exception to this was the plow test adjacent to Texas Flats, where deep plow penetration in medium density ($\rho \sim 0.25$ g/cm^3) hardened snow, combined with damaged equipment and a very rough ground surface, resulted in peak loads near 13 kN. The average drawbar force for this test was about 5.6 kN, well below the 13.4-kN limit. This exceeds the 5.4-kN estimate of the maximum drawbar force, but snow depths and densities encountered were greater than those projected. Snow density was 67% higher while snow depth was up to 17% greater than design.

Plowing with wheels, as previously mentioned, did not prove feasible, the main reason being tire flotation. Cross-sectional data showed plowed depths of from 15 to 20 cm. Penetration was within a few centimeters of the ice layer. If this ice layer had not existed, the denser snow beneath would likely

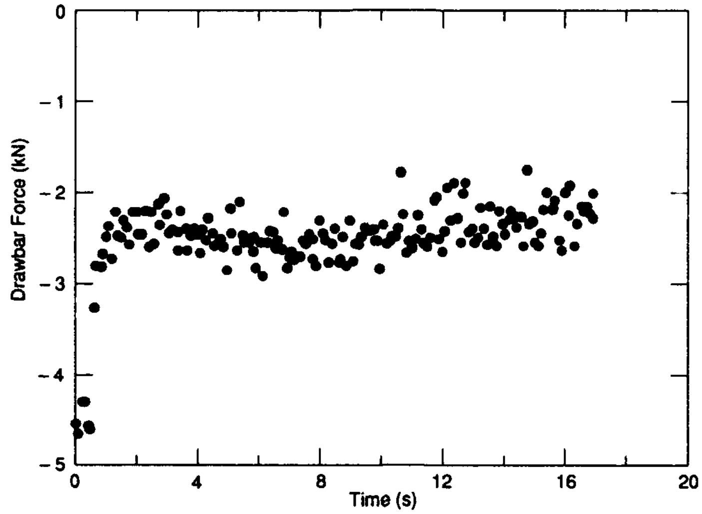


Figure 18. Forces from standing start.

have kept the plow from penetrating much farther. Drag tests in dense snow in Texas Flats showed only about 2 cm of sinkage of the wheels compared to 13 cm for skids. No useful drawbar data can be extracted from this test due to insufficient plow penetration.

Several tests using skids were run by replowing previously plowed paths. Again, the 15° maximum link angle limitation was encountered. Although less snow was removed above the ground, loads tended to be as high as when fresh paths were plowed because of the confinement of snow between the banks. Figure 17 shows this quite well. The photograph is from the first replow test, and thus shows the accumulation of snow as the test progresses. Successive tests had average drawbar forces of 2.5 kN.

One final observation is worth making. When starting from a standing stop with the plow fully engaged in the snow, testing showed that the breakout force, the maximum force attained due to static friction of the snow against the plow during startup, is approximately double the dynamic drawbar force. This test started from a standing stop and slowly accelerated to about 5 kph (Fig. 18). Again, forces are negative as they oppose the motion of the tractor. After the initial breakout, the force levels off as friction forces change from static to dynamic.

POST-TEST INSTRUMENTATION EVALUATION

Following testing at KRC, an evaluation of the instrumentation was performed. This included assessment of field performance and recalibration. The ultrasonic speed sensor remained at KRC for further evaluation by researchers there (Waineo and Osborne 1991).

The load cells operated trouble free during field tests. No failures of the sensors were recorded, although the analog input channel for one cell failed during baseline testing. This situation resulted from a problem with the DAS and was rectified by using another DAS input channel. Recalibration of the load cells was within 1.7% of pre-test calibration.

The ultrasonic speed sensor also operated well. Problems developed with the digital readout unit, but this problem was overcome by using the SUSV tachometer to maintain speed. DAS speed readouts on the last day of testing were faulty due to a loose wire on the instrumentation bus strip. The speed sensor worked well enough to be considered for use in further testing.

The tilt sensors were very unreliable and were not robust enough for field use. Three sensors failed outright during testing. Calibration checks at CRREL confirmed this. Fortunately, the sensors functioned long enough for some useful data to be obtained. From these data, we know that the top link angles for baseline and plowing tests were approximately 7° and 15°, respectively. Also, the rear SUSV unit was very near horizontal during plowing tests. Baseline and drag test data were normalized to 7° for all tests with <2% change in average forces. Similar results were obtained when plowing data were normalized to 15°. Not compensating for the top link angle affects the drawbar force by <4% from the calculated value. Therefore, although compensating for the link angle in drawbar calculations would have improved the data quality, using an estimated link angle in drawbar calculations did not adversely affect the data accuracy.

DESIGN CHANGES

Although overall performance of the half-width drag plow model was satisfactory, a number of improvements and design changes have been proposed for the full-scale model. A number of equipment failures occurred, including breakage of the front skid and failure of two different lifting mechanisms for the nose of the plow for highway travel. Both assemblies failed due to unanticipated high loads. A design flaw in the lift mechanism also inhibited raising the plow link, which would have improved depth of plow performance. Finally, the four-bar link needs to be redesigned to allow full depth of plowing in deeper snow conditions.

Failure of the front skid resulted from higher than anticipated loads that were caused by collision with large frozen masses of soil during plowing tests adjacent to Texas Flats. These high loads resulted in severe damage to the UHMWPE skid surfaces and breakage of the front skid at a weld. Calculations had been done using an anticipated maximum torsional force of 3.4 kN-m on the weld. According to Blodgett (1963), fillet size for a circular weld under these moment conditions is 6.4 mm, which was specified. During testing, however, forces in excess of 13 kN were encountered, resulting in breakage of the skid. A more robust skid assembly was designed and built during testing with no further failures. Solving the skid surface problem was only a matter of removing the UHMWPE. In the future, case-hardened steel skids will be used. Although the friction drag will be higher, this drag is not a significant enough component of the overall system drag during plowing to be consequential.

The lift mechanism caused several problems during testing. The original design did not prove strong enough for the task. When a heavier assembly was installed, failure again occurred, although at a different location. Due to the rough road surface over which the plow was transported, forces on the jacking link of the lift mechanism were high enough to cause buckling (Fig. 19). A stronger jacking link will be specified in future designs. In addition, the arm protruding over the nose of the plow interfered with the top link when the plow link was raised. A swing-down arm for the jacking mechanism would alleviate this problem.

To allow full penetration of the plow in medium to high density snow, as was encountered at KRC, the 4-bar parallel linkage needs to be modified. If a sinkage of the SUSV of 12 cm in 61 cm of snow and a desired plowing depth of 49.5 cm is assumed, a

Figure 19. Failure of jacking mechanism.

modification to the top and lower links is necessary. With the plow link raised to the upper position, the distance from the lower plow clevis to the bottom of the skid is 24.8 cm. The lower tractor adapter clevis is 28 cm above the bottom of the track of the SUSV (excluding grousers). When the SUSV sank 13 cm in the snow, the lower tractor plow link is 45 cm below the tractor clevis. To maintain a link angle of less than 15°, the link itself must be 1.75 m in length, as opposed to the current 1.25 m.

The rear wheels-to-skids conversion process also needs to be examined. Although the current method of replacing the wheels with the skids on the hubs is operable, it is not convenient, especially at low temperatures. Two possible improvements currently being considered are a reduction of changeover hardware, from the current five studs to one or two through an adapter mounted to the hub, and a bell crank assembly that would pivot between permanently mounted wheels and skids. The second option is currently being considered for the full-scale prototype plow.

A final aspect being considered is the low friction coating on the wings and skirt. The current covering, UHMWPE, works well but is difficult to apply and harder to repair. On the half-width model, the UHMWPE was attached to the aluminum with nylon screws. Since construction of the first prototype, a source for rubber-back polyethylene has been found. Although this would greatly facilitate initial fabrication, repair and resurfacing would still be difficult. A number of spray-on polyurethane coatings are currently under investigation for this use as well as application to front-mounted highway snowplows.

FULL-SCALE PROTOTYPE DRAG PLOW

With the successful completion of the field tests in January 1991 at Keweenaw Research Center, the full-scale prototype phase of the project was approved. Work for the fiscal year through September 1991 has included the design of a full-scale model based upon analysis of the half-width model, incorporating the changes discussed above, and an estimation of the loads, which will be discussed next. Construction of the plow commenced in October 1991, with testing conducted in Fairbanks, Alaska, in February 1992.

The test most closely resembling conditions in Alaska was that in the Texas Flats area of KRC on 17 January 1991 (test 17WH07). Snow density was in the 0.22 to 0.29 g/cm^3 range, compared to the 0.14 to 0.19 g/cm^3 range in the Alaska field trip. Snow depth was about 0.6 m as opposed to a 1.0 m design depth for Alaska. The estimated mass of snow displaced was 200 kg over the length of the plow. For a 16-cm ground clearance skid assembly, rather than the 13-cm arrangement on the half-width prototype, the depth of snow plowed would be 84 cm as opposed to 47 cm, an increase of 37 cm or 79% for the full-scale application. Plowed width will double from approximately 1.25 m to 2.45 m. The mass of snow displaced can be calculated from the half-width mass displacement using the following ratios:

Mass of snow (1/2 width):	200 kg
Density ratio:	0.62
Depth ratio:	1.79
Width ratio:	2.0

$$\text{Snow mass} = 200\,(0.62)(1.79)(2.0) = 443\text{ kg.}$$

This is approximately double the mass of snow moved for the half-width model.

Undercarriage drag for both models should be similar. Drag measurements taken in Texas Flats for the 13-cm skids were on the order of 1 kN, of which 25% was due to friction. If the friction force is quadrupled by doubling the plow size and skid height is increased 25% to 16 cm, drag will be about 2.4 kN. Predicted total force due to mass and drag is 6.8 kN for the full-scale plow.

Estimating the total drawbar pull for the full-scale model plow is not as straightforward. Looking at data from the Texas Flats area plowing trial, an average drawbar force (horizontal) of about 5.8 kN was required. Of this, about 2.8 kN or 48% of drawbar force is due to factors other than drag or mass of snow resisting motion. The most likely mechanisms acting to resist motion are the forces of shear and compaction of the snow along the path banks. Scaling forces to the full-scale model results in the following projected drawbar force:

Drag due to plow:	2.4 kN
Force due to snow:	4.4 kN
Accountable forces:	6.8 kN
Percent forces accountable:	52 % (from half-width tests)
Projected full-scale drawbar force:	6.8/0.52 = 13.0 kN.

As noted in the SUSV drawbar capability specifications, the limiting drawbar force for snow in excess of 0.6 m is 13.4 kN. The drawbar load for deep snow is thus ≈97% of design capability. This is very close to the towing limit in deep snow. A tandem–SUSV towing arrangement may be necessary in deep snow.

The doubling of the shear and compaction component of the load is conservative in the above calculations. With drier, less dense snow as is found in Alaska, shear and compaction forces should not be as high. As an example, during tests run in Alaska with a SUSV, sinkage in dry snow of a density of 0.2 g/cm^3 was 33 cm. At KRC, with snow density in the 0.31 g/cm^3 range, sinkage was ≈13 cm. SUSV ground pressure is 12 kPa. A 55% decrease in snow density resulted in doubling the compaction depth under a given load. This is predicted by the sinkage equation (eq 2), which states that a reduction of ρ by half will double the sinkage. The dryness of the snow also reduces adhesion, which will decrease the shear strength of the snow. Analysis of these snow characteristics is beyond the scope of this report, other than the assumption that the shear and compaction factors of the load will not be as significant a proportion of the full-scale model as they were with the half-width model. The 13.0-kN value obtained above should be an adequate design load for the full-scale model.

SUMMARY

The concept of a rear-mounted drag plow for use in clearing deep snow was proven in small scale and half-width model studies. The design concept incorporates a parallel linkage, limited degree of freedom 4-bar link connector between a V-plow and the motive vehicle, in this case the U.S. Army's small unit support vehicle (SUSV). Critical factors, including pitch and roll stability, depth of penetration, drawbar force, and the relationship between snow characteristics and plow performance, were investigated. The success of field trials in January of 1991 at Keweenaw Research Center, Hancock, Michigan, has led to approval for further work on a full-scale prototype drag V-plow capable of clearing a 2.4-m path in 1 m of low density snow to a depth of 15 cm above ground level. Projected maximum drawbar force for the full scale plow is 13.0 kN, 97% of the 13.4-kN limiting drawbar capacity for the SUSV in snow over 0.6 m deep. Design changes are currently being investigated to enhance performance and facilitate field use of the plow. Further investigations are currently being conducted on various low friction coatings for the plow surfaces. A patent on the plow and towing mechanism as has been applied for through the Army Corps of Engineers.

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APPENDIX A: ASSEMBLY DRAWINGS

The following assembly drawings depict major assemblies and components used with the half-width model tested at CRREL and KRC during 1990 and 1991. These drawings are not to scale. Use these drawings for reference to descriptions in the text only. They do not incorporate the recommended design changes covered in the text.

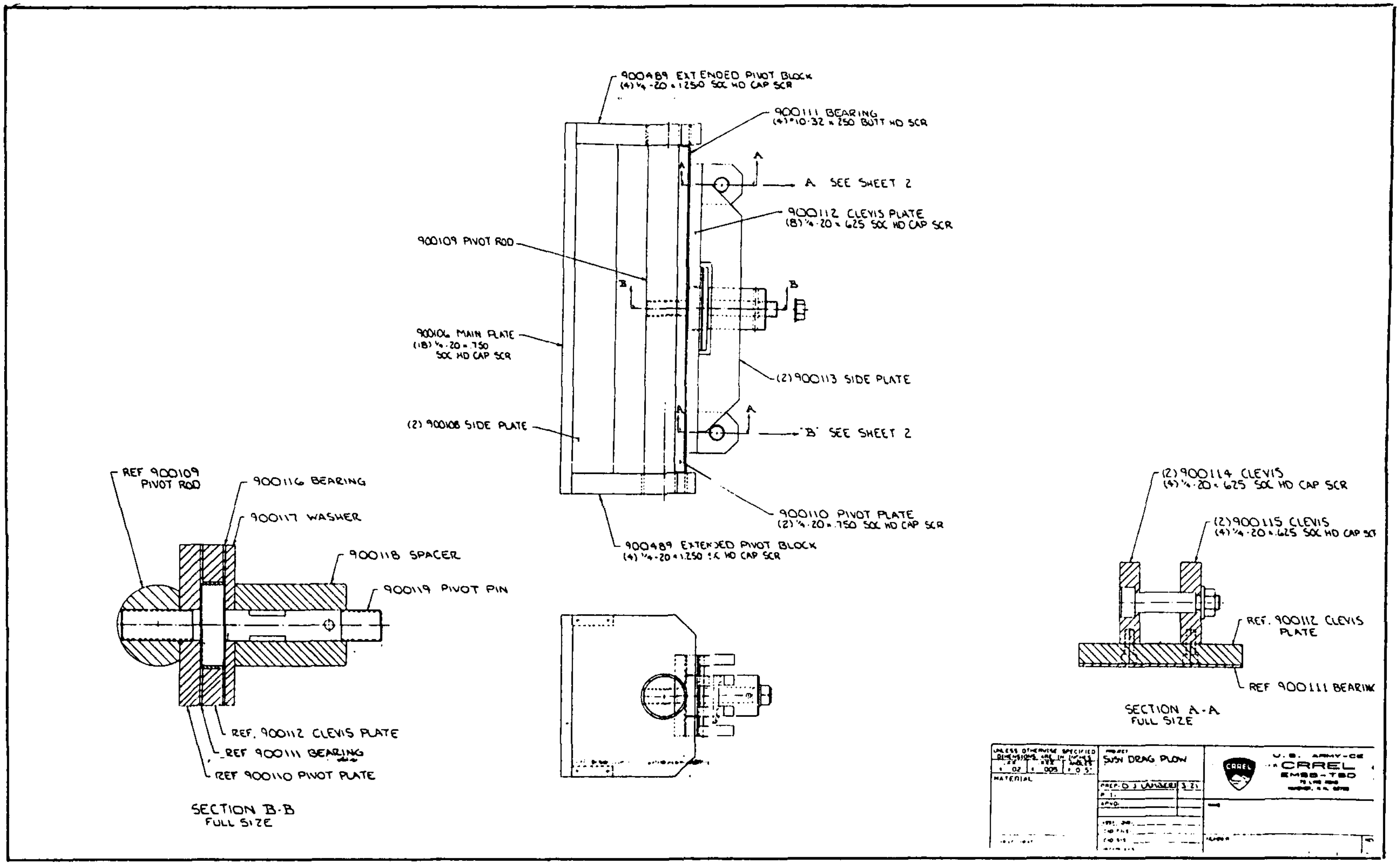


Figure A1. SUSV hitch with tractor (ground) link.

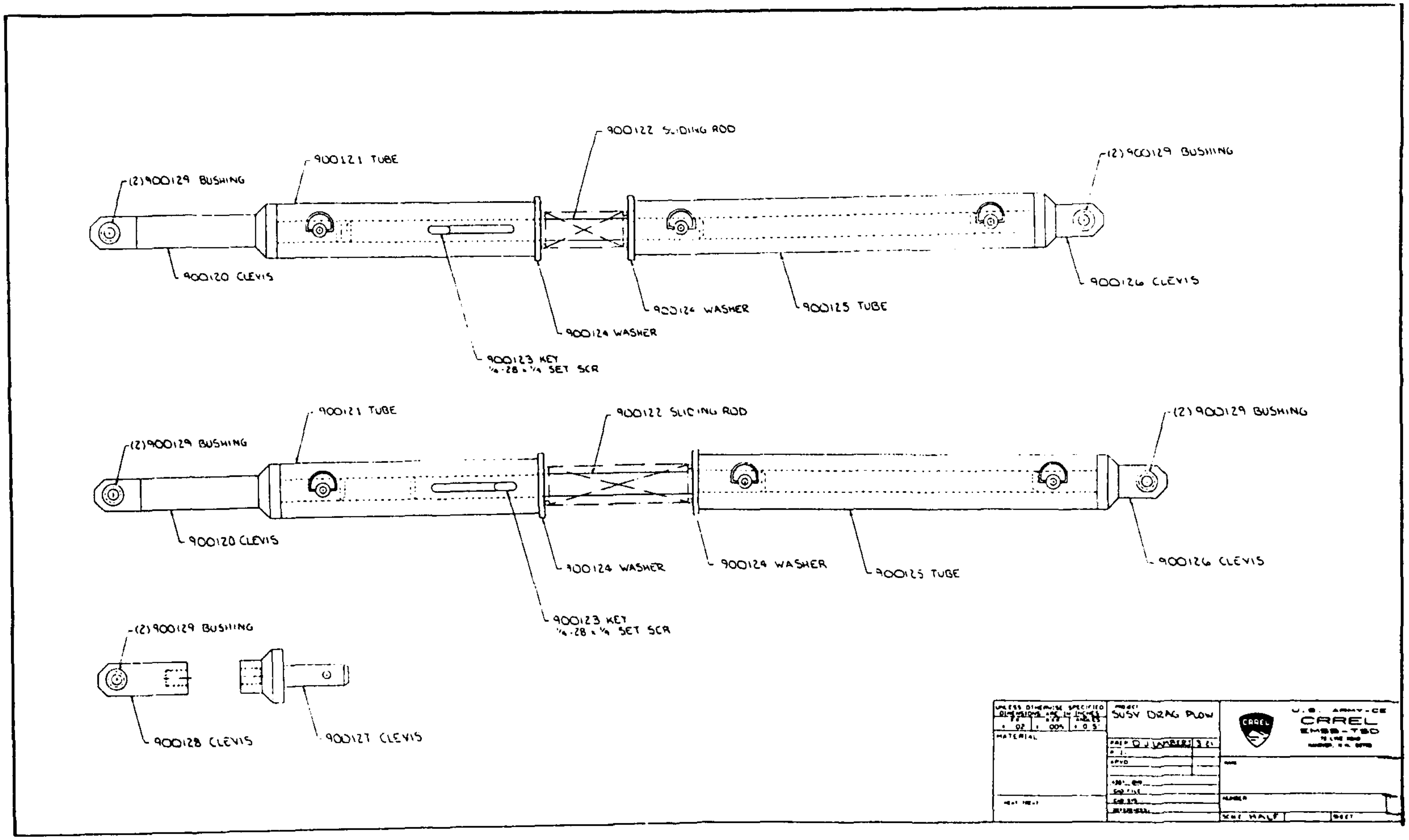


Figure A2. Top and lower links.

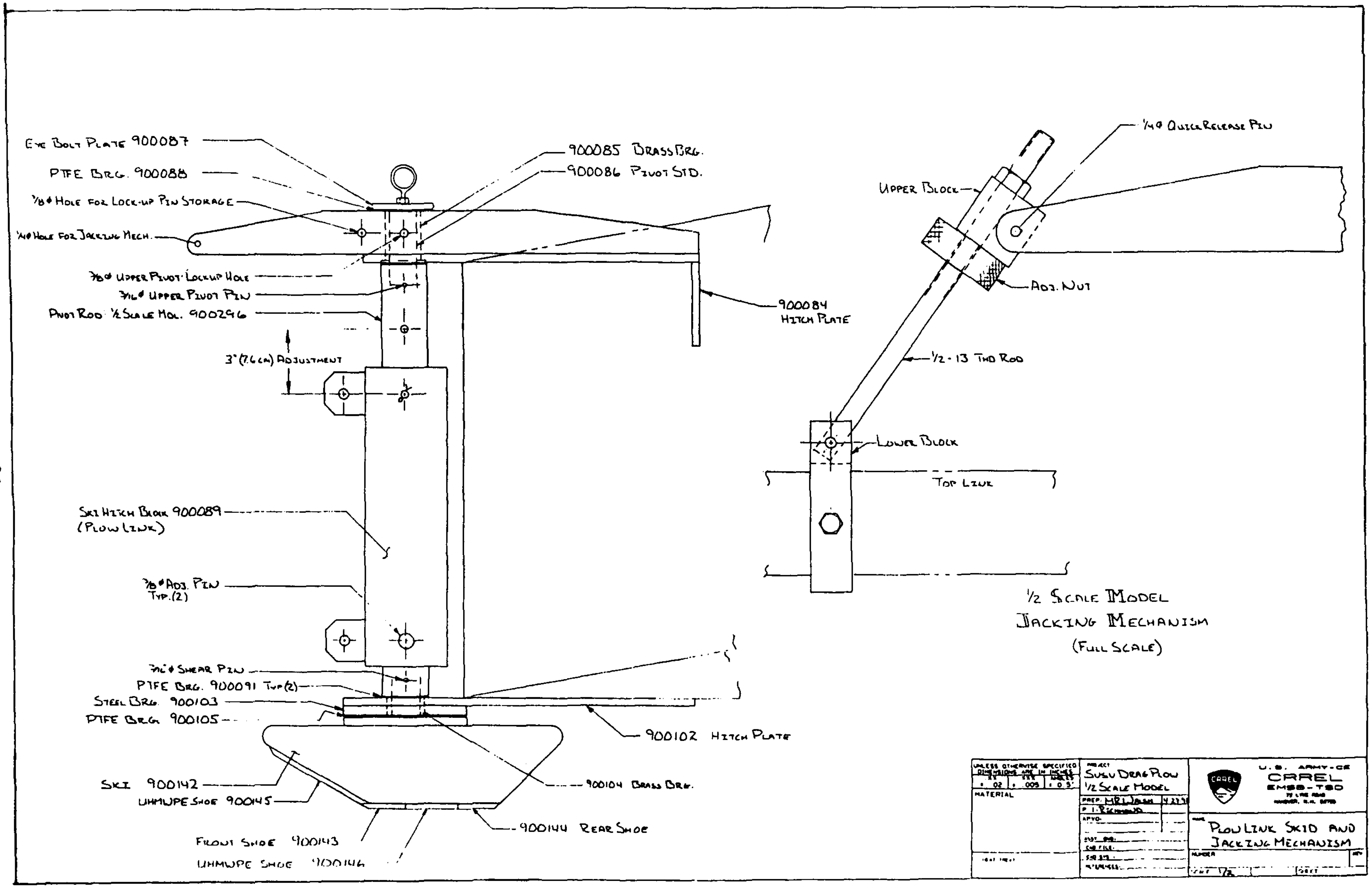


Figure A3. Plow link with skid and jacking mechanism.

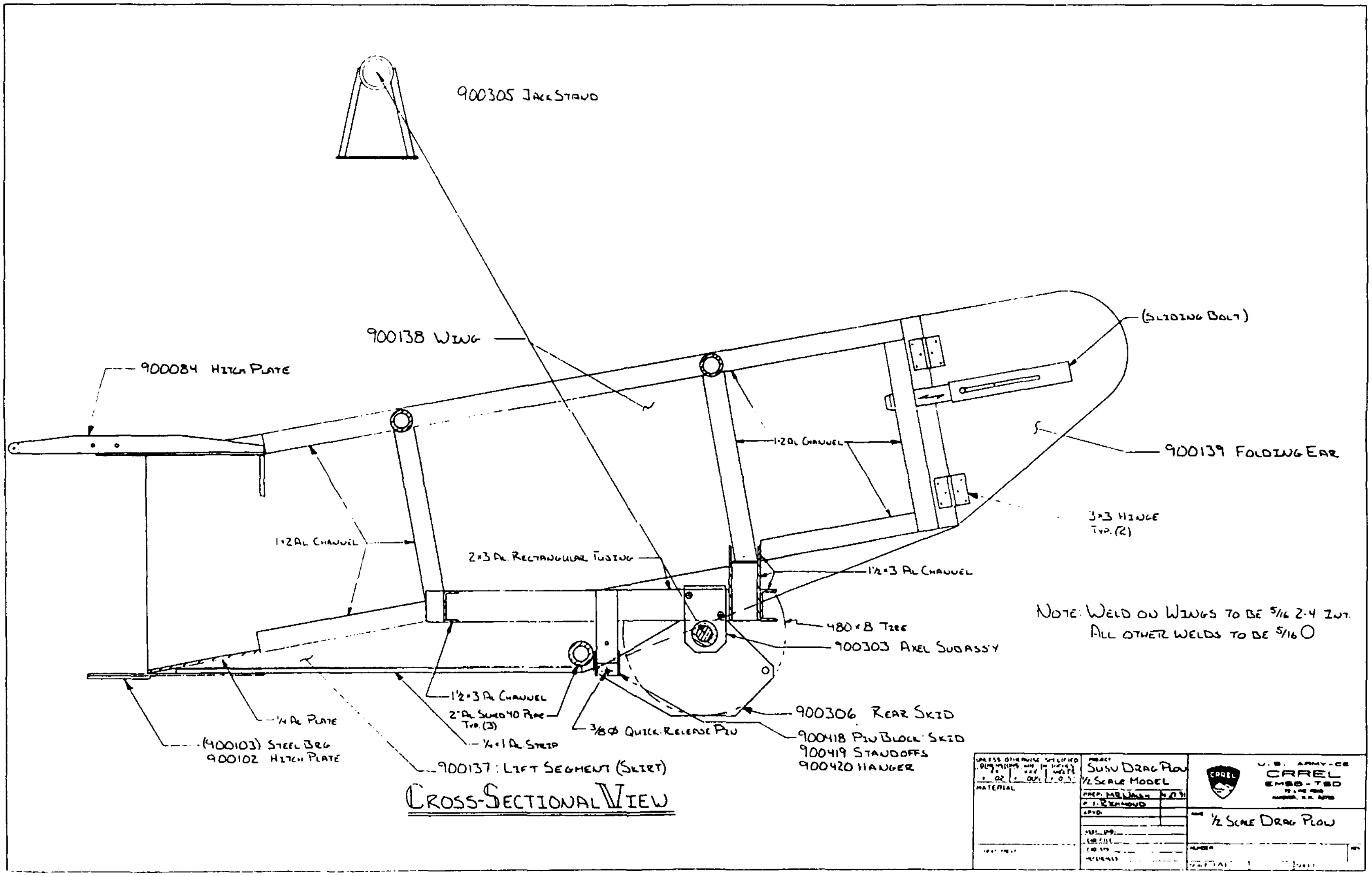


Figure A4. Cross sectional view of plow.

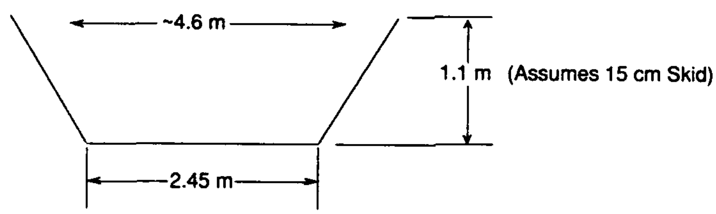
APPENDIX B: CALCULATIONS FOR PLOW GEOMETRY

The following calculations were done to derive the shape and geometric properties of the drag plow. Original calculations were done for the full-scale model, and were reduced for the half-width proof of concept model which was used in field trials described in this report. Center of gravity calculations were conducted before completion of the model for rear skid positioning. The original intent was to have equal weights on all three skids for similar penetrating force, but geometric constraints prevented this (the tires would interfere with the wings). Thus the skids were located as far forward as possible, with the front skid having 23% more weight than either rear skid. Analysis of the data from field testing showed this to be fortuitous, as the vertical component of the drawbar force was great enough to offset the static load on the front skid, contributing to the tendency of the plow not to penetrate to ground level. Adding weight to the plow did not change the plow performance noticeably, so this was not a critical factor in the plow performance.

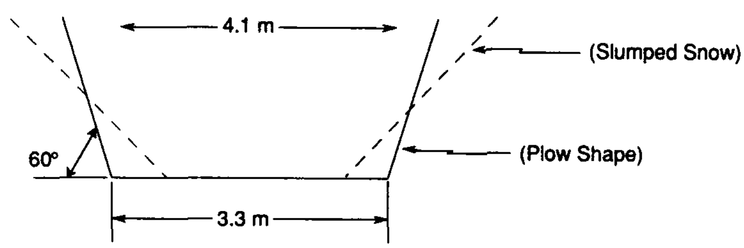
FULL-SCALE PLOW GEOMETRY CALCULATIONS

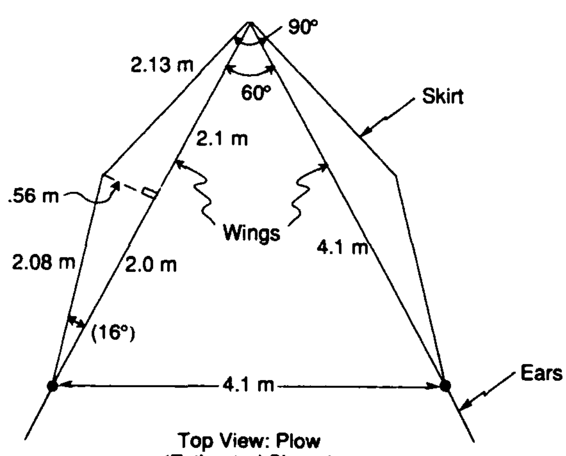
Plow design: pathway

Use 45° for Snow Angle of Repose
Use 1.2 m for Maximum Snow Height



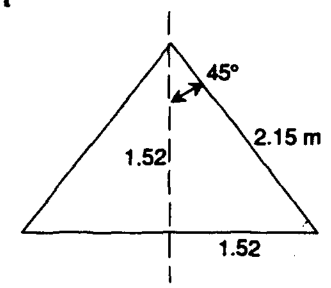
Finished Path Shape
Full-Scale Plow





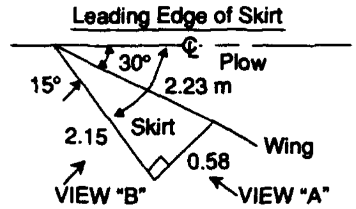
Top View: Plow
(Estimated Shape)

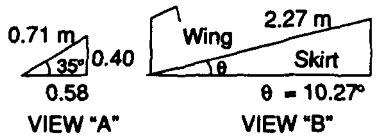
Skirt



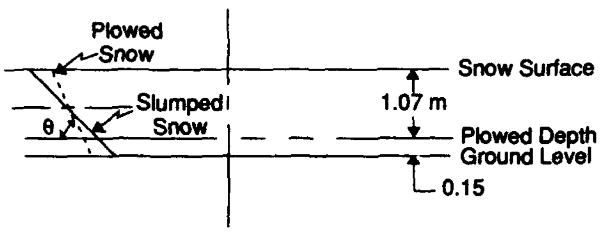
Base Plan

Snow Angle of Repose Estimated at Worst Case to be Equivalent to Dry Gravel, Which is Approximately 43°. Use 45°.





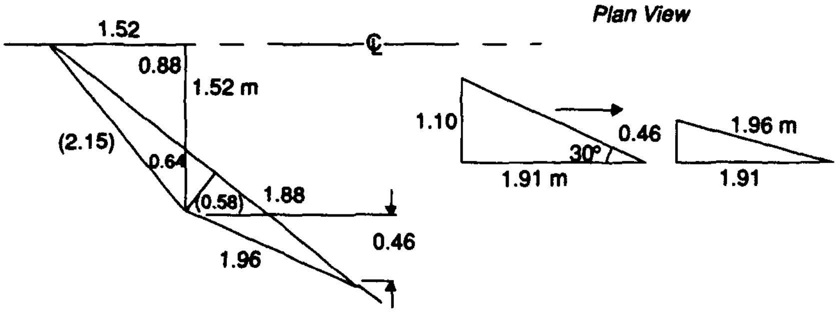
Trailing edge of skirt

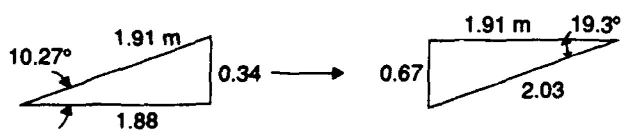


Molded Shape of Path Caused by Trailing Edge

$\theta = \tan^{-1}(2.33)$
$= 67°$
Use $\theta = 60°$

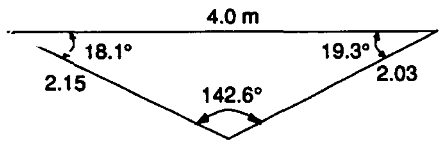
Plan View





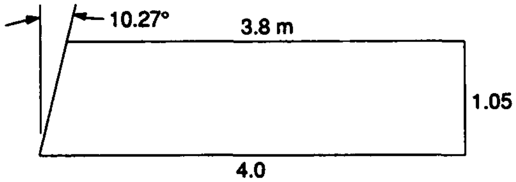
Orthogonal View

Pattern for skirt



Area = 1.33 m^2
Thickness = 0.95 cm
Weight = 34.3 kg

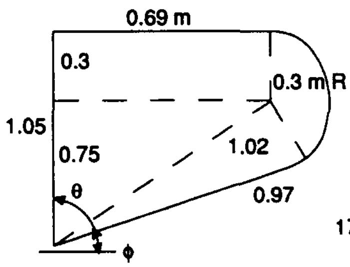
Main wings

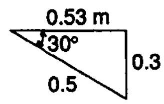


Area = 4.06 m^2
Thickness = 0.64 cm
Weight = 70.0 kg

Ears

(Use to Clear Snow an Additional 0.3 m)





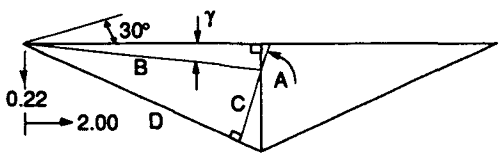
Add 0.19 m for ∢ to get 0.69 m

$17.4° + 42.97° = 60.375° = \theta$
$29.625° = \phi$

Area = 0.74 m^2
Thickness = 0.64 cm
Weight = 12.8 kg

CENTER OF GRAVITY CALCULATIONS

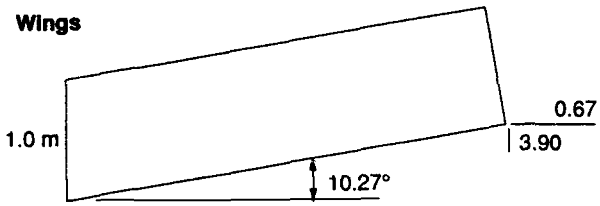
Skirt (see above)



$A = 0.22/\cos(18.1) = 0.24$
$B = (2^2 + 0.22^2)^{1/2} = 2.01$
$\gamma = \tan^{-1}(0.22/2) = 6.34°$
$C = B \sin(18.1 - 6.34) = 0.41$
$D = (B^2 - C^2)^{1/2} = 1.97$
$B' = 2.0$
$z = 0$ (Symmetric)
$y = C \sin 35° = 0.23$ m
$x = z \cos(36.34) = 1.61$ m

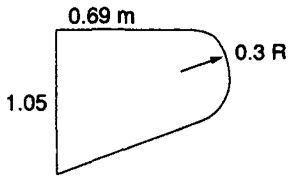
(Checked w/Anvil 1000 MD)
CAD Package

Wings



x = 1.90 cos 30 = 1.65 m = x
0.87 m = y
0 = z

Ears



x = [0.42 cos (10.27) + 3.90] cos 30 = 3.74 m

y = 0.94/cos (10.27) + 0.67 = 1.63 m

z = 0 m

(Checked w/Anvil 1000 MD)
CAD Package

Overall center of gravity of aluminum surfaces

X = [1.61 (2 × 34.3) + 1.65 (2 × 70.0) + 3.74 (2 × 12.8)]/235.9 = 1.85 m

Y = [0.23 (68.6) + 0.87 (140) + 1.63 (25.6)]/235.9 = 0.76 m

Z = 0

Note: Aluminum Surfaces Only: Full-Scale Dimensions

Half-scale center of gravity calculations

1) Plow structure (aluminum surfaces) from above:

$$\left.\begin{array}{l} x = 0.76 \text{ m from nose} \\ y = 0.38 \text{ m from base} \\ z = 0 \end{array}\right\} \text{Total Wt.} \sim 91 \text{ kg}$$

2) Pivot mechanism (actual wts)

Links:	11.8 kg	(1/2 of the 2 Links)
Pivot Bar:	11.3 kg	
Plow Link Block:	28.1 kg	
Skid:	3.2 kg	
	54.4 kg	total @ x = z = 0

3) Center of gravity of pivot mechanism (1) and structure (2)

x = 0.76 (91)/145.2 = 0.48 m
y = [0.38 (91) + 0.34 (54.4)]/145.2 = 0.37 m
z = 0

4) Add 0.48 cm UHMWPE to plow surface

Skirt:	16.3 kg
Wings:	49.5 kg
Ears:	9.1 kg
	74.9 kg (75 kg)

5) Estimate for bracing: 40 kg

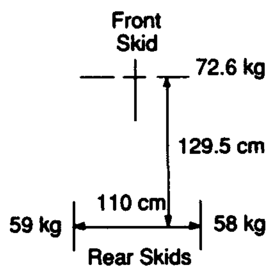
Assume Bracing Equally Distributed About Plow Center of Gravity
Total Weight of Plow Now = 260 kg

6) Calculated center of gravity

$X = [0.76\ (127.0) + 0.82\ (75.0)]/260 = 0.61$ m
$Y = [0.38\ (127.0) + 0.37\ (54.4) + 0.39\ (75.0)]/260 = 0.38$ m
$Z = 0$

Note: Need to Add ~ 0.12 m to Y for skids.

7) Actual center of gravity measurements of completed plow



$X_{Act} = 0.63$ m (w/in 3%)

$Z_{Act} = 0$ m

Y_{Act} not obtained

Actual Total Weight, Including Mount: 253 kg (w/in 3%)

APPENDIX C: STRESS CALCULATIONS FOR CRITICAL PLOW ELEMENTS

The following stress calculations were conducted on critical plow elements to ensure integrity of the design. The towing mechanism, consisting of the tractor adapter, the links, and the plow pivot assemblies, was designed and analyzed to full scale specifications. The remainder of the plow used half-width parameters. All dimensions are SI except hardware, which is in English units. Environmental parameters, especially snow conditions, were assumed to be similar to those encountered in Alaska during field investigations, an assumption which, in normal years, would have been valid. During field tests in January at KRC, relatively high temperatures greatly densified the snow to the point where foot travel on the surface was possible (in Alaska, we generally sank into the snow halfway between our knees and hips). Ground surface conditions were also much rougher than anticipated, resulting in failure of the front skid. Several large mounds (>0.5 m) of frozen earth were encountered, one of which sheared the skid off. Field redesign of this member alleviated this problem. Failure of the jacking mechanism was caused by traveling with the mechanism engaged on the rather rough access road, a well-used snow road, at high speed. The plow would bounce enough for the rear wheels to leave the ground, causing severe impact loading of the jacking link. This was the member which eventually failed. Redesign of these two elements will remedy the problems encountered at KRC.

STRESS CALCULATIONS

1) Pintel Attachment (Tractor Adaptor)

a) Bolt Requirement: 26.5 kN Total Tractive Force

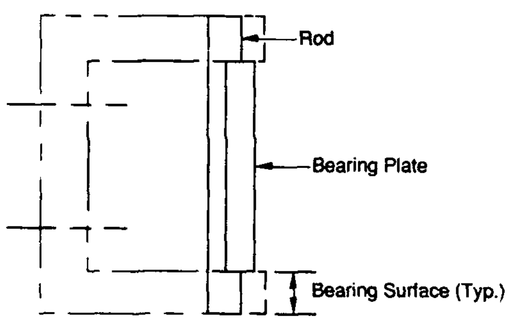
Best to Use Stainless for Ease of Removal (Corrosion)
Assume Full Force on One Bolt (Worst Case)
Pintel Mount Holes 1.3 cm diam.
Load Limit for 3/16 in. UNC Hex Hd Cap Scr. = 30.4 kN

- Use 1/2 UNC 316 SS Hex Hd Cap Scrs. (Qty. 4)

b) Yaw (Swivel) Bar

Use SS Shaft Material (For Brg. Purposes—Corrosion)
$\sigma_y = 240$ MPa $\sigma_s = 145$ MPa
For Shear, Need Area of ~3.23 cm^2 $\Rightarrow$ 1 cm Radius

- Need to Mount a Bearing Plate so Use 5.08 cm diam.



c) Bearing Material

Yaw

Want Non-Lubricated Journal Bearing w/Low Coefficient of Friction (μ).
SS on Bronze: $\mu = 0.35$
SS on Duralon: $\mu = 0.10$ (Teflon/Dacron Brg.)

- For 44.1 kN Load on 5 cm diam. Brg. Use 2.5 cm long.

Roll

Same Requirement as Above.
Teflon on Steel: $\mu = 0.04$ (Static)

d) Roll Stud

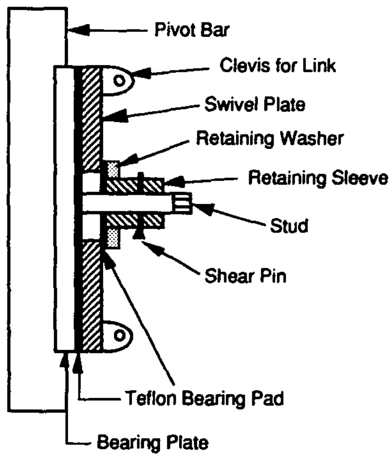
Design for 40.2 kN Load (1.5 × max. load)
Use SS Stud (Brg. & Corrosion Considerations)
Try Tensile Area for 5/8–18 thd (Calculations in inches)

$A_T = 0.7854\,[0.625 - (0.9743/18)]^2 = 0.26$ in.^{2} (1.67 cm^2)

$A_T = 1.67$ cm^2

$\sigma_y = 240$ MPa

$F_{max} = 40.6$ kN > 40.1 kN



- Need Shear Pin to Protect Equipment and for Quick Attachment/Detachment of Plow.

Maximum Force: 40.6 kN (from above)
Use 0.63 Diam. 17-4 PH SS Shear Pin (2 × 45 kN Rated)

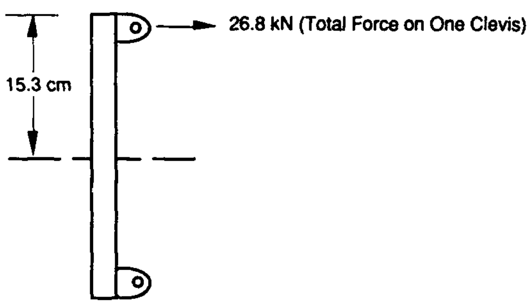
e) Swivel Plate

M = 4.08 kN-m

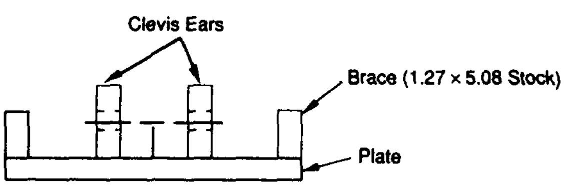
$$\frac{Mc}{I} = \frac{2.08 \times 10^3 (1/2\,h)}{1/12\,b\,h^3} = \sigma$$

For b = 1.27 cm, h = 5.08 cm (Standard Stock–4130)

σ = 316 MPa, < 738 mPa, σ_y for 4130



Brace Swivel Plate to Strengthen in Bending



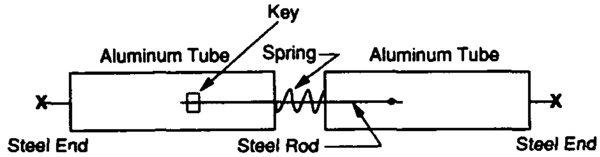
- Use 1/2" ϕ 303 SS Shoulder Screws for Clevis Pins: 246 kN Shear Capacity.

2) Top and Low Links

Max. Load: 26.8 kN

σ_y (4340 Steel) = 695 MPa
σ_y (6160 Aluminum) = 280 MPa

General shape



a) Tensile Analysis

$\sigma = F/A$

Steel: 695 = 26.8/A | A = 3.86 cm | R = 1.1 cm (0.44")

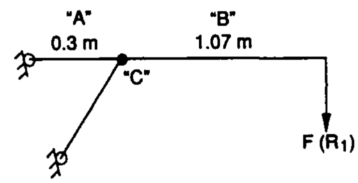
- Use 1" (2.54 cm) Diam. Rod

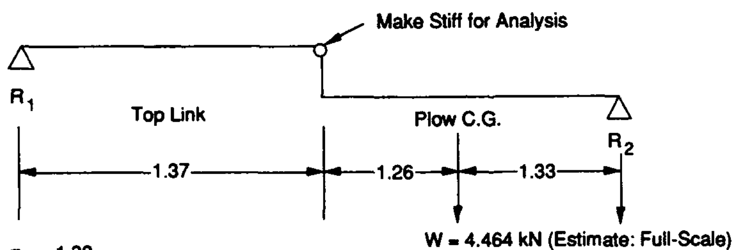
Aluminum: 2.80 = 26.8/A | A = 9.57 cm | R_i = 1.27 cm
R_o = 2.07 cm

- Use 2" OD x 1" ID (5.08 O.D. x 2.54 I.D.) Tube

b) Bending (Due to Jacking Mechanism)

Link Length: 1.37 m
Analysis Model
Need F (R_1)





$R_1 = \frac{1.33}{3.96} = 1.50$ kN
$R_2 = 2.96$ kN

Shear Load Over "B" = 1.5 kN
Bending Moment: R_1 (1.07) = 1.5 (1.07) = 1.6 kN–m at Pin "C"
Check Strength of Aluminum Tube

M = 1.6 kN–m

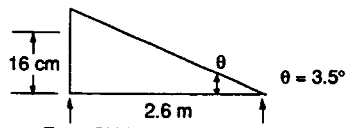
$$I = \frac{\pi}{64}\left(D_o^4 - D_i^4\right) = 3.06\times10^{-7}\,m^4$$

$$\sigma = \frac{Mc}{I} = \frac{1.6\,(.025)\times10^3}{3.06\times10^{-7}} = 1.305\times10^8 N\ m^{-2} = 130.5\ MPa < 280\ MPa$$

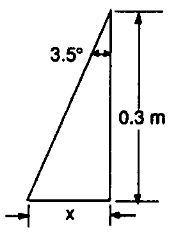
- Aluminum Tube Safe in Bending

c) Compensators

Necessary Deflection for 16 cm Obstacle



Link Compensation



$x = 0.3 \tan(3.5)$

$= 2$ cm

Need at Least 2x for Safety

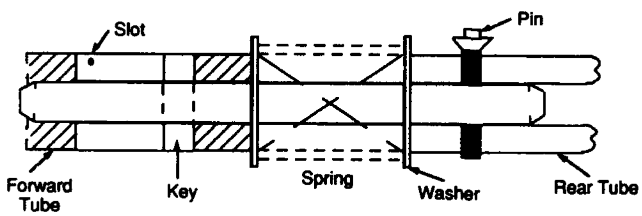
From Century Spring Catalog:

# 3744: $\Delta L = 6.9$ cm	$k = 1.9$ kN/cm
# 4337: $\Delta L = 5.6$ cm	$k = 1.0$ kN/cm

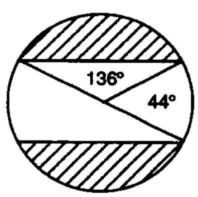
Use # 4337 for Half-Scale Applications,

3744 for Full-Scale Applications

Both Springs Have ID 2.56 cm

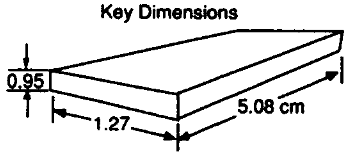


Need to Check Key:



Rod End View

Key Dimensions



Rod Area Required for Tension = 0.42 cm^2

Area of Circle (Rod) Segment:

$A = 1/2\, R^2 (\theta - \sin\theta)$

$= 1/2\,(1.61)\,(2.374 - \sin(2.374))$

$= 1.35\ cm^2$

- Sufficient for 3x Load

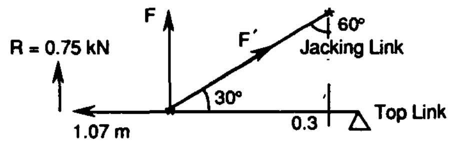
Shear Force of 44.6 kN

Required Key Area for Shear = 1.08 cm^2

3) Road Link (Jacking Mechanism)

Design for 1/2 Scale

Buckling



$F = 2.6$ kN

$F' = F/\sin(30°) = 5.2 \text{ kN} = \dfrac{\pi^2 EI}{\ell^2}$ (From Roark)

$E = 207$ GPa (GN/m^2)

$I = 1/4\ \pi R^4$

$\ell^2 = 0.0162\ \text{m}^2$

$F' = [\pi^3 (207 \times 10^9)/4\ (0.0161)]\ R^4$

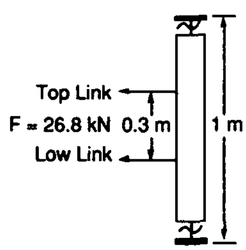
$= 9.97 \times 10^{13}\ R^4$

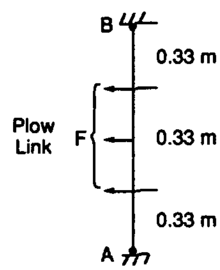
For $F' = 5{,}200$ N $R = 0.0027$ m $= 0.27$ cm

- Use 1.28 Diam. Steel Rod (2 × F.S.)

4) Plow Link (Full-Scale)

Bending





Model

$R_A = R_B = \dfrac{26.8}{2} = 13.4$ kN

$\sigma = F/A \quad \sigma_s \approx 0.6\ \sigma_y$

$M_{max} = 26.8 \left(\dfrac{0.5}{1}\right)\left(\dfrac{1}{3} + \dfrac{1}{3(2)2}\right) = 5.58$ kN-m (Worst Case)

Stress due to Moment

Hollow Shaft: $64\ Mc/\pi \left(D_o^4 - D_i^4\right)$

Solid Shaft: $64\ Mc/\pi\ D^4$

Look at 4340 Hollow Bar ($\sigma_y = 1.05$ GPa)

$1.05 \times 10^{12} \overset{?}{=} 5.58 \times 10^3 (64)\, c / \pi \left(D_o^4 - D_i^4\right)$

For Worst Case, $c = D_o/2$. Try $\left.\begin{aligned} D_o &= 0.057 \text{ m} \\ D_i &= 0.038 \text{ m} \end{aligned}\right\}$ Standard Stock Size

$c = 0.029$ m

$1.05 \times 10^9 \overset{?}{=} 5.58 \times 10^3 (64)(0.029)/\pi\, [(0.057^4) - 0.038^4]$

$= 10{,}356 / \pi\, (8.47 \times 10^{-6})$

$1.05 \times 10^9 > 0.4 \times 10^9$ • 2 1/4" OD x 1 1/2" ID 4340 OK (Plow Link Support Bar)

Twisting

Assume Max $\tau = 26.8 \times 10^3 \times 0.33$ N-m
$= 8.9$ kN-m

For Hollow Shaft: $\sigma_\tau = 2\tau r_i / \pi \left(r_i^4 - r_o^4\right)$

Max @ Outer Boundary...

$\sigma_\tau = 2(8.9 \times 10^3)(0.029) / \pi\, (0.029^4 - 0.019^4)$
$= 0.165 \times 10^3 / 5.77 \times 10^{-7} = 0.29 \times 10^6$ kN

$0.63 > 0.29$ • 2 1/4" OD x 1 1/2" ID 4340 Still OK
(Using Shear Strength in Torsion Calculation)

Shear

Use Same Hollow Shaft as Above...

$\sigma_s = 0.63 \times 10^9$ N/m^2
$\sigma = F/A = 13.4/0.0018 = 7.6 \times 10^6 = 7.6$ MPa
7.6 MPa << 630 MPa

Bending w/Twisting

$M' = 1/2\left(M + \sqrt{M^2 + T^2}\right)$ Max $\sigma = \dfrac{M'r}{I}$ $r = 0.032$ m

$T' = \sqrt{M^2 + T^2}$ Max $\sigma_s = \dfrac{T'r}{I}$ $I = 6.04 \times 10^{-6}\, m^4$

Bending Moment Fixed at 5.58 kN-m Max.

Back-Calculate Allowable Torsion Load Using Given Relationships:

$\sigma_s = 0.63 \times 10^9 \text{ N/m}^2 = \dfrac{T'r}{I} = T'\left(5.3 \times 10^3\right)$

$T' = 119$ kN-m

$T' = \sqrt{M^2 + T^2} = 119 \times 10^3 = \sqrt{\left(5.58 \times 10^3\right)^2 + T^2}$

$T = 118$ kN-m Max. Allowable Torsion

$M' = \frac{1}{2}\left(M + T'\right) = \frac{1}{2}(5.58 + 119) = 62.3$ kN-m

$\sigma = \dfrac{M'r}{I} = \dfrac{62.3 \times 10^2 (0.032)}{6.04 \times 10^{-6}} = 330$ MPa

- Should Use Shear Pin to Protect Drag Linkages

5) Shear Pin

Location: Where Front Skid Attaches to Plow Link

a) Check @ Center of Links

Rod ϕ = 2.54 cm

Material 4340

$M = F \times D = 2F/3$

$\sigma = \frac{Mc}{I} = \frac{2}{3} F \frac{0.0254}{2} / \frac{\pi(0.0254)^4}{64}$

$\sigma = 414.4 \times 10^3$ F

For $\sigma = 1.05 \times 10^9$ N/m^2, F = 2.5 kN/bar

For Two Links, Need 5 kN for Yield

M = 0.69 x 5 = 3.4 kN-m on Vertical Shaft (Plow Link)

b) Check at End of Link

M = 3.4 kN-m

Links are ϕ 0.0572 x ϕ 0.038 m

σ = Mc/I = 3.4×10^3 (64) (0.029) / π (8.47×10^{-6})

= 0.24 GPa < 1.05 GPa

Pin to Shear at 0.038 m Diam.

F = 3.4 kN-m/0.038 m = 89.5 kN (20,000 #)

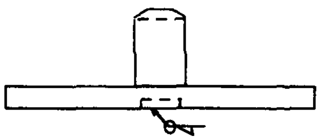
Need High Safety Factor Due to Critical Nature of Drag Links.

Use $f_s \sim 4$: F ≈ 22.5 kN (5000 #)

- Use 0.48 cm (3/16" ϕ) Diameter 17–4 PH SS Shear Pin

6) Front Skid

Weld—Aluminum



Weld Size

Joint in Torsion $f = TC/J_w$ $J_w = \pi d^3/4$ (Blodgett)

$J_w = \pi (0.038)^3/4 = 4.3 \times 10^{-5}$ m^3

$f = 855 (0.019)/4.3 \times 10^{-5} = 378$ kN/m on Weld

- Need 6.35 mm Weld Leg

7) Upper Support Arm (Jacking Mechanism)

Length = 0.2 m, Width 5.0 cm, Height = 5.0 cm

Material = Aluminum 6061 Std. Stk.

Force on End: 0.75 kN

Try Uniform Strength Cantilever Beam (Depth = d)

$d^2 = (x/L)\, h^2$ — h = Height = 0.05 m (at Root)

L = Length = 0.2 m

$d^2 = .0125\, x$

Use Tapered Rather Than Parabolic Form

At 1/2 L,	x = 0.1 m,	d = 0.04 m	Use 0.05 m
1/3 L	x = 0.066 m,	d = 0.03 m	0.04 m
1/4 L	x = 0.05 m,	d = 0.025 m	0.03 m

Strength

Cantilever Root — $M_{max} = FL = 0.75\ k \times 0.2 = 150$ N-m

$$\sigma = \frac{Mc}{I} = 150(0.025)/0.05^3/12 = 360\,\frac{kN}{m^2} < \frac{280\ MN}{m^2}$$

Rest of Beam Will Have Lower Stress

APPENDIX D: TEST AND CALIBRATION INSTRUMENTATION

Load cells

Manufacturer	Sensotec
Model	AL411 RM 10000
Serial numbers	248818 (Top link)
	247588 (Lower link)
	278621 (Spare)
Range	0–10,000 lbf (44.5 kN)
Excitation	10 V DC
Output	2 mV/V
Accuracy	± 0.2% full scale
Repeatability	± 0.05% full scale
Overload protection	150 %
Operating temperature range	–54° to 120°C
Temperature compensation range	–20° to 100° C

Tilt sensors

Manufacturer	General Oceanics
Model	6020
Serial numbers	0172 (Top link)
	0166 (Plow)
	0169 (SUSV rear unit)
Range	±90°
Excitation	5 V DC
Output	±2.5 V
Accuracy	±0.1%
Repeatability	Not stated
Overload protection	Not stated
Operating temperature range	–10° to 70°C
Temperature compensation range	NA*

Speed sensor

Manufacturer	Micro-Trak Systems, Inc.
Model	MT-3000
Serial number	Not obtained
Range	64 to –32 kph
Excitation	12 V DC
Output	11.36 Hz (Counts) per m/s
Accuracy	±1.5% > 0.06 kph
Repeatability	Not stated
Overload protection	Not stated
Operating temperature range	–30° to 50°C
Temperature compensation range	No compensation

Digital protractor

Manufacturer	Lucas Sensing Systems
Model	DP-45
Serial number	00310001
Range	±45°
Excitation	9.0 V DC (Battery)
Output	LCD
Accuracy	0.1°

Repeatability	±0.1°
Overload protection	Not stated
Operating temperature range	0° to 65°C
Temperature compensation range	NA

Calibrated load cell

Manufacturer	BLH Electronics
Model	U1C
Serial number	79253
Range	±26.8 kN
Excitation	6 V DC
Output	2.4 mV/V
Accuracy	0.25% of RO
Repeatability	0.05% of RO
Overload protection	Not stated
Operating temperature range	–35° to 115°C
Temperature compensation range	–10 to 45°C

* Tilt sensors were located in heated enclosures maintained between 5° and 10°C.

APPENDIX E: SKID CONFIGURATION TESTS

Test data in graphical form are presented in CRREL Internal Report 1098. This appendix contains the data acquired for tests run with skids mounted on the rear two support points. Data are presented in four parts: Drag, baseline, plowing, and replowing. Data for each test are presented in the following forms: Drawbar force vs. test elapsed time, drawbar force vs. speed, and speed vs. elapsed time. Force was graphed as negative as it opposed the tractor (SUSV). Not all tests contain all test parameters due to faulty instrumentation. A synopsis of the tests with skids follows.

Drag tests

17WH05	Baseline (Drag): Skids, Texas Flats: 10 to 13 cm of packed snow, density ≈0.4 g/cm3. No sinkage of SUSV beyond grousers. Skids dug in to plow base, a depth of 10 to 13 cm. Aluminum front skid with UHMWPE intact. Average speed was 5.5 kph, with an average force of –1.1 kN. Low ambient temperature (–5°C). Straight line test.
17WH06	Baseline (Drag): Skids, Texas Flats: See 17WH05 for details. Average speed: 5.1 kph. Average force: –1.1 kN. Curved path test.

Baseline tests

19SKT01	Baseline: Skids, Access Road: Packed snow road with a density of ≈0.4 g/cm^3. No sinkage of SUSV beyond partial cleats. Skid sinkage of 2.5 cm front, <2 cm rear. Front skid badly damaged from previous day's testing off Texas Flats. UHMWPE very rough. Average test speed was 4.8 kph with an average drawbar force of –0.6 kN. Average force at 1.9 kph was –0.64 kN. Warm ambient temperature (4.5°C).
19SKT02	Baseline: Skids, Access Road: See 19SKT01 for general parameters. Average speed for this test was 4.8 kph with an average drawbar force of –0.63 kN. A very good test at speed.
19SKT03	Baseline: Skids, Access Road: See 19SKT01 for general parameters. Average speed for this test was 8.2 kph with an average drawbar force of –0.51 kN.
19SKT04f	Baseline: Skids, Access Road: See 19SKT01 for general parameters. Average speed for this test was 8.1 kph with an average drawbar force of –0.61 kN.
19SKT05f	Baseline: Skids, Access Road: See 19SKT01 for general parameters. Average speed for this test was 1.9 kph with an average drawbar force of –0.59 kN.
19SKT08f	Baseline: Skids, Access Road: See 19SKT01 for general parameters. Average speed for this test was 1.8 kph with an average drawbar force of –0.63 kN.
19SKT09	Baseline: Skids, Access Road: See 19SKT01 for general parameters. Average speed for this test was 11.1 kph with an average drawbar force of –0.46 kN.

19SKT11f	Baseline: Skids, Access Road: See 19SKT01 for general parameters. Average speed for this test was 11.4 kph with an average drawbar force of –0.65 kN.
26J09f	Baseline: Skids, Access Road: See 19SKT01 for general parameters. New steel front skid with no UHMWPE. Cold ambient temperature (–11°C). Communications difficulties caused poor test speed stability. Average speed for this test was 4.2 kph with two acceleration/deceleration cycles and an average drawbar force of –0.32 kN.
26J10f	Baseline: Skids, Access Road: See 26J09f for general parameters. Average speed for this test was 4.8 kph with an average drawbar force of –0.26 kN.
Plowing tests	
17WH07f	Plowing: Skids, Off Texas Flats: Snow depth of 40 to 70 cm, with an air temperature of around –11°C. Snow temperature was –7°C. Snow density ranged from 0.22 to 0.29 g/cm^3. SUSV sinkage was about 25 cm (estimated). The plowing depth varied from 51 cm in the less dense snow to 25 cm where the plow left the undisturbed snow and entered a stretch of obstacles and machined snow (ρ = 0.34 g/cm^3). This area was very rough with brush and large clods of frozen soil. The front skid was lost on one of these frozen mounds, while the rear skids' UHMWPE bases were damaged. Plow depth can be well correlated with snow density and SUSV sinkage. Average speed during the test was 5.1 kph, while the average force was –5.4 kN. Average force at 1.9 kph was –3.7 kN.
19SKT12f	Plowing: Skids, Test Road Circle: Snow depth in this area was 23 to 46 cm. The air temperature was 2°C while the snow temperature was –6°C. Area has many snowmobile tracks and some SUSV tracks made the previous day. Snow density was in the range of 0.3 g/cm^3 in the undisturbed areas, while it approached 0.4 g/cm^3 in the trafficked areas. SUSV sinkage was 14 cm. Snow density below the SUSV track was 0.4 g/cm^3. The snow on the surface was wet and sticky, and held together and packed well when disturbed. Front and rear skids were damaged from testing done at Texas Flats on the 17th. Plow penetration was almost to ground level. Average speed was 5.0 kph, while average drawbar force was –3.0 kN. Tested in a straight line.
19SKT13f	Plowing: Skids, Test Road Circle: See 19SKT12f for general parameters. Minimum turning radius test across several snowmobile and SUSV tracks. Plow penetration almost to ground level. Average speed was 5.0 kph, while average drawbar force was –2.6 kN. Very stable while cornering.
19SKT14	Plowing: Skids, Test Road Circle: See 19SKT12f for general parameters. Straight line test parallel to road. Snow denser, but no quantitative check made. Snow depth 30 to 60 cm, becoming deeper as the test progressed. Average speed was 5.0 kph, while average drawbar force was –2.1 kN (–1.6 kN in shallow snow to –3.1 kN in the deeper snow).

26J11f Plowing: Skids, Test Road: These tests were conducted on an unplowed section of the Test Road. Snow depth was 40 to 70 cm. Air temperature was –11°C and snow temperature –12°C. Windy conditions prevailed. The snow density varied widely with depth. The top 20 cm was light, with $\rho \approx 0.2$ g/cm^3, underlain by an ice layer ($\rho = 0.9$ g/cm^3) 0.6 cm thick. The snow density below the ice was between 0.36 and 0.39 g/cm^3. This road had been previously trafficked by snowmobiles, as evident from the density measurements. SUSV sinkage was 15 to 18 cm, strongly influenced by the ice layer. Penetration of the plow into the snow varied according to SUSV sinkage but was on the order of 23 to 28 cm. Average speed was 5.1 kph with an average drawbar force of –1.6 kN. Average plowed depth was 24 cm. Test was run in a straight line down center of road.

26J12f Plowing: Skids, Test Road: See 26J11f for general parameters. Tests run to one side of the road. Speed varied from 0 to 1.7 kph. At low speeds, 0 to 0.32 kph, the average force was –2.2 kN. At higher speeds, 0.6 kph, the average force was –2.4 kph. Plowed depth averaged 28 cm, increasing as the test progressed, but not correlating with speed. Force did correlate with depth.

26J13f Plowing: Skids Test Road: See 26J11f for general parameters. Test speed started at 4.8 kph and decreased to 0 kph. Force at speed was –2.6 kN, while residual force on the plow when stopped was –2.1 kN. Plowed depth averaged 28 cm.

26J14f Plowing: Skids, Test Road: See 26J11f for general parameters. Test speeds ranged from 0 to 6.3 kph. For creeping speed (<0.3 kph), drawbar force was ~–2.6 kN, while at the higher speed, it dropped 0.2 kN to –2.4 kN. Plowed depth averaged 26 cm.

26J15f Plowing: Skids, Off Test Road: See 26J11f for general parameters. Snow depth was 43 to 61 cm. Area was rough, brushy, and seemed relatively undisturbed compared to where the road was located. The main segment of the test was run at 3.2 kph, with a corresponding average drawbar force of –3.6 kN. Average force for the test as a whole was –3.1 kN at 3.4 kph. Good plow penetration was evident (>36 cm), with SUSV sinkage in the 20- to 25-cm range (estimated). As with the test off Texas Flats, several frozen clods were encountered, but the plow righted itself and dug back in. A few bushes were mowed over in the process. The test was conducted over a sweeping curve. No damage to the front skid occurred.

28JAN03f Plowing: Skids, Texas Flats: Tests conducted in snowdrift along one edge of field. Air temperature was –16°C, with –10°C snow temperature. Very windy conditions. Radio headset failures crippled communications, and a wiring fault interrupted speed data acquisition, resulting in rather poor tests. Snow density was 0.18 g/cm^3, very close to the snow density in Alaska. Snow depth was 25 to 38 cm, with plowed penetration to ground level. Target speed was 1.6 kph. The average plowing drawbar force was –1.1 kN. Snow lifting rather than compaction seemed to be the dominant mechanism of removal.

28JAN03f Plowing: Skids, Texas Flats: See above for general parameters. Snow depth for this test was 25–50 cm. Plow penetration to ground level. Target speed was 1.6 kph, and average force was –1.6 kN.

Replowing tests

26J16f Replowing: Skids, Test Road: These tests were reruns over previously plowed paths that had not sufficiently cleared on the first pass. Residual snow averaged 25 to 40 cm in depth, with a density of 0.4 g/cm^3. Plow skids penetrated to within 3 cm of the ground surface. Average speed was 4.9 kph, with an average force of –2.5 kN. Force increased as the test progressed, reflecting a buildup of snow in the pre-plowed path. It ranged from –1.3 to –3.8 kN.

26J17f Replowing: Skids, Test Road: See 26J16f for general parameters. Residual snow in path was 27 cm (14 cm to be plowed). Test was run from 0 to 1.9 kph. Starting force was –1.3 kN, leveling off to –2.7 kN at 4.9 kph. Cleaned up path to within 4 cm of ground (skids).

26J18f Replowing: Skids, Test Road: See 26J16f for general parameters. Test was run at low speed (≈1.6 kph). Average force was –2.3 kN. Cleaned up path to within 4 cm of ground (skids).

APPENDIX F: WHEEL CONFIGURATION TESTS

Test data in graphical form are presented in CRREL Internal Report 1098. This appendix contains the data acquired for tests run with wheels mounted on the rear two support points. Data are presented in three parts: Drag, baseline,and plowing. Data for each test are presented in the following forms: Drawbar force vs. test time, drawbar force vs. speed, and speed vs. time. Drawbar forces are presented as negative as they oppose the motion of the SUSV. Not all tests contain all test parameters due to faulty instrumentation. A synopsis of the tests with wheels follows.

Drag test

17WH03 — Baseline (Drag): Wheels, Texas Flats: 10–13 cm of packed snow. $\rho \approx 0.4$ g/cm^3. No sinkage of SUSV beyond grousers. Plow nose skid dug in 10+ cm, wheels sunk in <2 cm. Aluminum front skid with UHMWPE intact. Test was low speed wit:. several accelerations and decelerations around the 2.6 kph target speed. Loads at 2.6 kph were ~–1 kN.

Baseline test

26J01f — Baseline: Wheels, Access Road: Packed snow road with $\rho \approx 0.4$ g/cm^3. No sinkage of SUSV beyond cleats. Plow nose skids (steel with no PE) dug in ~1.5 cm. Average test speed was 5.3 kph. Average test load at 2.1 kph was –130 kN.

Plowing test

26J19 — Plowing: Wheels, Test Road: Top 20 cm of snow cover low density (0.196 g/cm^3), followed by a 0.6 cm layer of ice (ρ = 0.9 g/cm^3). Dense snow (0.37 to 0.4 g/cm^3) lay between ice layer and ground surface. Average speed of SUSV during test was 4.5 kph, with 2 acceleration/ deceleration cycles. Average force at speed (4.8 kph) was –1.6 kN. Plowed depth was ~20 cm, or down to the ice layer.

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13. ABSTRACT (*Maximum 200 words*)

Winter logistical operations employing wheeled vehicles are severely restricted because of traction losses in deep snow. To enable the use of wheeled vehicles for off-road winter deployment, an independent drag-plow was developed to be attached to the pintel mount of the U.S. Army's small unit support vehicle (SUSV). Small-scale testing revealed significant stability problems with a towed wedge-shaped plow model. Geometric modifications to the plow design and a 4-bar parallel motion towing linkage were developed to stabilize plow roll and pitch, respectively. A welded aluminum half-width model incorporating these modifications was successfully tested at Keweenaw Research Center in northern Michigan in January 1991. Parameters measured during testing included pitch and roll angles, drawbar forces, speed, plowed path geometry, and snow characteristics. These parameters were used to determine the feasibility of a full-scale model capable of plowing a 2.45-m path in 1-m-deep low density snow, leaving 15 cm of snow as ground cover.The model performed well in medium density snow, with drawbar forces in the 5.6-kN range. Plow penetration was limited by a geometric constraint of the 4-bar linkage, with 15° the approximate maximum link angle from horizontal. Pitch and roll stability in off-road applications was excellent, with the plow demonstrating an ability to right itself and dig in after encountering obstacles. Successful half-width tests have proven the concept of utilizing a SUSV-towed V-plow for clearing access roads in deep snow for off-road winter operations. Data extrapolation of half-width tests demonstrates that a full-scale plow is feasible.

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